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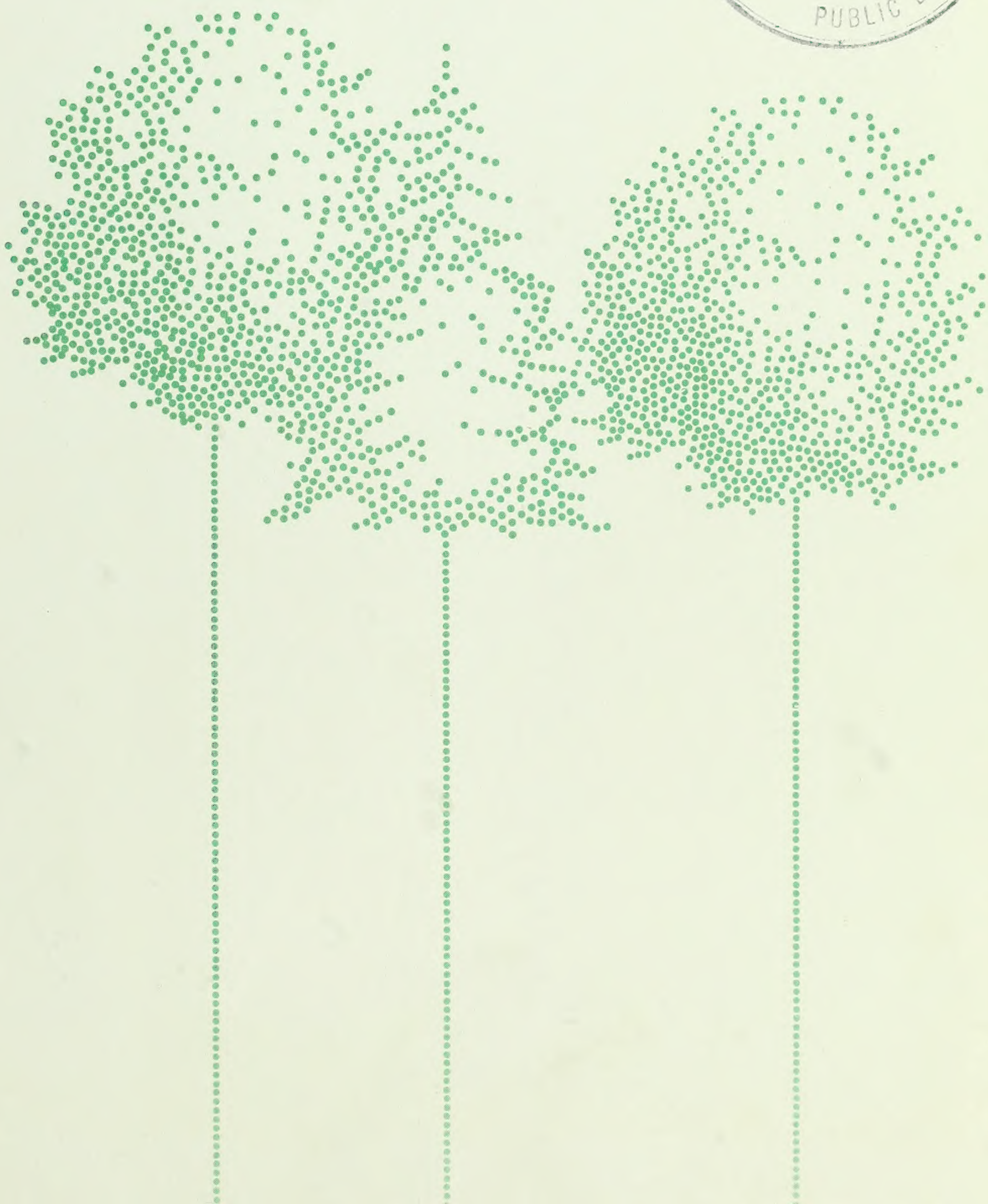

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CONTENTS

3. MULTI-CLASS MODELS

4. DISTRIBUTION AND WHOLE STAND MODELS

5. BIOMATHEMATICAL/PROCESS MODELS

6. REGENERATION MODELLING

7. CHARACTERIZATION OF SITE QUALITY

8. EFFECTS OF CLIMATE, INSECTS, DISEASE, AND ANTHROPOGENIC DISTURBANCE

9. MODELLING FERTILIZATION AND GENETIC IMPROVEMENT

Contents are continued in Volume 2

MODELLING FOREST GROWTH: APPROACHES, DEFINITIONS, AND PROBLEMS

David Bruce and Lee C. Wensel[1]

ABSTRACT. The greatest difference among growth models is in regularity of stand. Irregular stands require detailed description of individual trees and are seldom successfully simulated by simple models developed for regular stands. Irregular-stand models can be used for regular stands with increased computation cost and possible loss in precision. We suggest some consistent definitions of terms used to describe development of growth models. High correlations among variables in growth studies, incomplete assessment of factors affecting growth, and other problems are hard to deal with when analyzing forest growth and constructing growth simulators.

INTRODUCTION

Fourteen years ago, IUFRO meetings in Canada and France considered computer simulation of forest growth. Those meetings were timely because by 1973 expanded use of computers permitted detailed analyses not previously possible of the relations among growing trees. The year 1973 also is important to the authors of this paper because it is close to the time we started work on growth simulators. DFIT by Bruce (Bruce et al. 1978) and CRYPTOS and CACTOS by Wensel (Wensel et al. 1986, Wensel et al. 1987) were entirely different in philosophy, structure, and purpose. Perhaps by combining our experiences, we will produce a broad perspective on forest growth simulation.

Munro's (1974) paper on forest growth models is a starting point for a fresh look at growth simulation. His discussion of modelling philosophy set the stage for much recent progress, but seems best remembered for its classification of growth models which singles out one of several differences among models--whether it is a single-tree or a whole-stand model.

In this paper, we suggest emphasis on the forest condition being modelled and on the purpose of the model. We also examine some terms that are frequently used in forest growth and yield modelling. Finally, we look at some problems often encountered in developing computer simulations.

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APPROACHES TO GROWTH MODELLING

The greatest difference in models of forest conditions results from the regularity of the forest stand to be simulated. Stands with uniform progressions of frequencies in size-classes allow use of different models than stands without them. Many even-aged stands have unimodal diameter distributions easily described by a great variety of frequency functions; recently, the Weibull distribution has been popular (Bailey and Dell 1973). The classical J-shaped distributions of all-aged stands can be approximated by the negative exponential function (Leak 1965). More complex arrays of sizes can be represented by combinations of two or more regular distributions (Depta 1974). Munro mentioned only the potential use of diameter distribution models, possibly because two of the earliest were described at the meeting at which he gave his paper (Burkhart and Strub 1974, Clutter and Allison 1974).

In regular stands, density and hence competition can be evaluated on a stand basis in terms of stem volume, basal area, number of trees, or crown volume. In these stands, each tree's share of competition depends mostly on its size, and typically a single measure of size characterizes the tree quite well. To model most stands that are irregular, the growth of each tree must be estimated individually. No single tree characteristic will adequately express a tree's growth potential or its response to competition; information about surrounding trees is often required as well. The common solution is to list for each tree the elements that determine its future growth, such as species, tree size, crown size, and even previous growth rate. These characteristics are then used in growth predictions. This technique can be used for regular stands, but models suitable for regular stands seldom can be used successfully for irregular stands. Using a more complicated model than necessary often has at least two costs: greater computational expense and a loss in precision of estimates.

In stands that are quite irregular, no single measure of stand density will serve to represent the competition affecting individual trees. This problem can be resolved by subdividing the stand and measuring local density. Theoretically, the best solution may be to use a distance-dependent single-tree model of growth where the size, vigor, and proximity of neighboring trees are evaluated. These models are still being studied and, despite the high cost of developing and running them, they have the potential for reasonable statistical accuracy, which may or may not be realized ultimately.

Relationships among trees are not so simple that they can be completely defined by description of neighboring trees and distances to them. Because of localized genetic similarity, stand histories, and root-grafts, not all trees grow independently. Also, roots capture unoccupied space faster than do branches (Smith 1986). Sometimes competition from low vegetation--in young stands, in stands on soils with low water-holding capacity, and in areas with low rainfall--is as important as crown competition in limiting tree growth. Consequently, there are places where stem size and stocking level are more effective than complicated measures of crown extent in assessing competition for empirical growth models.

In studies where measures of stand density and competition have been compared, expensive point measures often have added no useful information to the easily derived stand measures. Some studies ignored stand measures and compared only point measures; others merely compared the two kinds of measures without testing how much information point measures might add to that provided by stand measures (Alemdag 1978). Even the latest comparisons should not be accepted as definitive for all stands, because most of them were made in plantations or even-aged stands where competition usually is reasonably uniform (Daniels et al. 1986). More critical tests eventually will be made in stands with mixed ages and several species.

Prospective uses influence choice of models. If only an estimate of total volume of wood at some early date is needed, all that may be required is a projection of past trends in total volume or a simple survey of changes in average stand volume, with little attention paid to stand regularity. If only a prediction of change in inventory by size class of material is needed, anything more complicated than a size-class model is unnecessary. If, however, some estimate of change in quality is needed, each tree may have to be treated individually in the computer model, even in a uniform, even-aged stand, particularly if forest stand structure changes during the simulation period. Comparisons of alternative treatments, especially those not previously applied and observed, put heavy pressure on any model, no matter how it was developed.

SOME QUESTIONS OF DEFINITION

Munro (1974) suggested a major difference among forest-growth modellers is that some use "analytic" and some "empirical" models. Today, the major distinction is between "process" and "empirical" models. In their text on regression analysis, Draper and Smith (1981) call them "functional" and "predictive" models. The term "analytic" is commonly used to certify the virtue of either a model or its author.

Process models simulate the biological processes that convert carbon dioxide, nutrients, and moisture into biomass through photosynthesis. These estimators have apparently not been developed yet to the stage where biomass and biomass growth can be identified as individual cells and cell-wall thickening and aggregated into trees with detailed dimensions of interest to forest managers (Ford 1981). "Empirical" is not used here to describe a model resulting from a fishing expedition by a neophyte wearing a blindfold; many models that estimate tree sizes use mathematical functions well suited for describing biological processes. They are "empirical" because they are based on periodic tree measurements, and make no attempt to measure every factor that may affect tree growth.

The link between process and tree-growth models will be made, but not soon. Meanwhile, parallel use of such models can check consistency of two independent estimates of total wood production. Such compatibility also should be sought among empirical models with various levels of detail--simply because stand growth is the sum of growth of its individual members.

The driving elements of process models and empirical models are quite different. The process model may use direct measurements of growing-season precipitation, hours of sunlight, and other details. An empirical model also uses these variables, but indirectly because it assumes that the average of these conditions will prevail in the future. If a measure of fertilizer application is added to each of these models, they should agree on the estimated response for the observed period. The process model also may be able to estimate the response with a different amount of precipitation or other climatic change. This is an example of what we consider to be use of a "black box" in the simpler model. Black boxes fall short of complete explanation but may provide unique and less expensive approximations (Leary 1975). Other examples of black boxes are substituting the path of the stand average for tracks of individuals, the use of empirically established asymptotic limits, substitution of direct estimates for more complicated algorithms, and even some kinds of stratification.

The concurrent development of many kinds of growth models in various parts of the world has created inconsistencies in definitions that lead to some difficulty in understanding unfamiliar growth models. Also, between forest managers (many with little formal statistical training) and biometricians (many with little formal forestry training), a gap in understanding often occurs when it comes to describing models or the modelling process. Likewise, gaps in understanding may exist between those dealing with even-aged forest stands and those dealing with all-aged or many-aged stands. The gaps between models and the real world cannot be cured by definitions, but only by a better appreciation of the modelling process. Developing such understanding among prospective users is one of the modeller's critical responsibilities.

Standard definitions should reduce some of the confusion that exists in the terms used to describe the process of developing, adjusting, and testing empirical forest growth models. Here are our suggestions:

<u>A model</u> is a mathematical function, or system of functions, used to relate actual growth rates to measured tree, stand, and site variables.

<u>Estimation</u> is the statistical process of deriving coefficients for models to define the growth rates as a function of measured tree, site, and stand variables.

<u>Verification</u> is testing a model with the data on which it was based to eliminate lapses in programming logic, flaws in algorithms, and bias in computations.

<u>Calibration</u> is adjusting a model to local conditions that may differ from those on which the model was based.

<u>Validation</u> is testing a model to see how well it predicts. Whenever possible, it is tested against independent data sets.

<u>Monitoring</u> is the continuing check of output of the system to detect shortcomings of the model.

Evaluation is considering how, where, and by whom the model should be used, how the model and its components operate, and the quality of the system design and its biological realism.

Simulation is using a growth model to estimate development of a stand through time under alternative conditions or cutting practices.

Models should be verified as a step in the statistical analysis used to produce the models' estimates. Often, calibration is done to sharpen predictions, either for a subset of the original data or for an independent data set. Calibration, however, can be dangerous when it is based on tenuous assumptions not supported by as profound observation and analysis as the original estimate. Some validation can be done as part of the fitting process, using covariance to isolate distinct data sets, but it may be done by a third party with an independent data set to decide whether to use the model (Reynolds et al. 1981). Validation is usually limited to small data sets because large data sets could be the basis for new models. Monitoring is done by responsible managers, even with the most sophisticated and best tuned simulators. Although verification, calibration, and validation are usually done by the modeller, model evaluation should be done by the user--who is responsible for accuracy of the prediction (Buchman and Shifley 1983).

The sequence of steps inherent in these definitions exemplifies the modelling process, with many of the steps repeated as users gain experience with the models. Discussion and refinement of these definitions should lead to less ambiguous descriptions of the model development process.

PROBLEMS IN CONSTRUCTING GROWTH MODELS

Although empirical growth models differ widely, common basic elements appear in most of them. Estimates are made of the changes with time of tree diameter, height, form, volume, or all of these variables, and also change in the number of trees per unit area. Added to these driving functions are the housekeeping functions, such as volume estimates based on tree height and diameter. The driving functions are based on tree species, age, land quality, climate, area history, and vegetation present. If the estimate is for a single species in a limited geographic area, other species are excluded and the current climate and prevalent soils of the area are included by default.

Other common elements in most empirical growth models are two dichotomies. First the separation of increment into potential and modified, and then the use of two kinds of growth modifiers. The potential growth, a basic change rate, is estimated by an equation that expresses biological development. This estimate is then modified by a function that serves to limit or accelerate growth. Changes in number from mortality (where there is too much competition) and regeneration (too little), may be at the extremes of modified growth. The two kinds of modifiers in use are internal, determined by stand development and built into the model, and external, resulting from management decisions or other factors external to the model, such as forest fires or pest epidemics. Some management decisions can be handled by the model

(thinning or fertilizing) but require special signals to activate the estimates. Other external modifiers are handled by returning to square one; harvest, regeneration, or both.

Growth studies seem to be plagued with some recurrent problems. One of the most common is the high correlation among variables measured in growth studies. These correlations are the result of allometric relations among the dimensions of living organisms and are not indications that true cause and effect have been identified. These high correlations make it easy to substitute convenient measurements for fundamental measurements. In many applications, this is a blessing--we customarily use DBH when diameter at some other height theoretically would be a better estimator--and get good results. Inadvertent substitution of crown volume for extent of the root system illustrates the mental confusion and biologic illusion possible in some growth analyses.

We are tempted to recite a long list of analysis problems we have met and overcome but this audience might not find such a list useful. Any good biometrician can warn of the dangers of overspecification of independent variables and the effects of near singularities or multicollinearity on coefficients in regressions and the strange estimates that may result. Only experience will shield against mystification by the manufacture of complicated indexes or estimators that appear to explain something in the data set being manipulated. Good modellers rely more on knowledge of silvics and principles of biologic growth than on statistical tests in selecting models and developing algorithms.

A common problem we see is testing the wrong hypothesis when generating driving functions. A favorite test is done by withholding a fraction of the data, to show that the regression performs satisfactorily on data not used in generating coefficients. If single random data sets are split in two halves, you can expect the estimates to differ at the 5% level in about one trial in twenty. These odds change in messy data sets. The real question that should be examined is whether or not totally independent data sets will be estimated satisfactorily. We have found it helpful to identify sources of batches of data, and use covariance to test differences among batches. This test gives some indication whether the estimates will perform correctly in circumstances other than those for which they were generated; the first test offers no clues about this, although it is used in some other kinds of validation (Snee 1977).

Another problem is the overconfidence of some modellers in the sophistication of their models. Computer programs excel in rapid and often accurate interpolation. This accuracy leads to the notion that simulators are indeed tracking biological systems, and, because of this and the knowledge and skill used in developing them, they can be trusted to extrapolate beyond the limits observed and measured (Burkhart 1975). The best thing that can be said about such extrapolations is that they suggest interesting hypotheses. Real-world observation is the only way to validate such predictions.

When modellers start work, they may be overwhelmed by data--most of it describing conditions commonly observed today--but unfortunately incomplete, poorly edited, and in some peculiar format. The modeller's problem is obtaining high-quality data for conditions critical to good estimates of coefficients and for conditions that may prevail in the future. Identification of current gaps in knowledge may be one of the most important steps in developing computer simulators; it should lead to more effective silvicultural research.

FINALLY

The above comments are gleaned from many years of growth and yield research. They are based on a small sample of the problems we faced in modelling during that time. Model building is an art because we seldom gain full knowledge of the system under study. Models are going to be put to uses not planned by their authors, enough data of the right design are never available, the variables used in the model are not measured on all of the trees or plots, and opportunities for verification, calibration, and validation are limited. Finally, some users may care little about the quality of the model and, instead, are fascinated by the beauty and completeness of the tables generated. All these things, particularly the last, put added responsibility on the researcher to place limits on the possible estimates and to explain adequately the output of the models created.

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SOME IMPORTANT ASPECTS IN THE DEVELOPMENT OF A MANAGED STAND GROWTH MODEL FOR WESTERN HEMLOCK

D.M. Hyink, W. Scott and R.M. Leon[1]

ABSTRACT. Discussed are the authors' experiences in developing a model for forecasting growth and development of managed stands of low elevation western hemlock (Tsuga heterophylla [Raf.]) in Oregon, Washington and British Columbia. Problems commonly encountered with data compiled from multiple research organizations such as inconsistencies in height sampling, differing measurement standards, and understanding and evaluating the importance and impact of ingrowth are discussed. The model architecture and such key elements as mortality estimation, mathematical compatibility between dominant height, site index curves and heights by dbh in stand tables, and necessary properties of thinning algorithms are presented.

INTRODUCTION

Although Douglas-fir (Psuedotsuga menziesii [Mirb.] Franco var.menziesii) is the leading commercial forest species in the Pacific Northwest, the importance of western hemlock (Tsuga heterophylla [Raf.]), albeit secondary, is nonetheless significant. Recognizing the need to add managed stand forecasting capability to the Company's "Single-Acre Forestry Planning Systems" (Depta, 1984), we undertook a project with the objective of using existing research data to build a flexible model to forecast the growth and development of plantations and managed natural stands of western hemlock under different levels of management. In this paper, we will discuss data compilation and preparation, review the model architecture, derive a size-density based mortality model, and outline some important considerations for thinning algorithms and consistent height prediction.

DATA

The "secondary regional importance" of western hemlock notwithstanding, a principal reason for the absence of a major modelling effort for this species was that no single research organization had a data set with sufficient breadth to accomplish such a task. This was also the case with Douglas-fir prior to the efforts of J.D. Arney and R.O. Curtis, who, with the help of thirteen contributing organizations, compiled the data which ultimately resulted in DFSIM (Curtis, et al., 1981). Data for our project resulted from a similar cooperative compilation.

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COMPILATION

In early 1985, eight research organizations (British Columbia Ministry of Forests, Crown Zellerbach (now Cavenham Forest Industries), ITT-Rayonier, MacMillan Bloedel Ltd., State of Washington (DNR), U.S. Forest Service (PNW Station), University of Washington Regional Forest Nutrition Research Project (RFNRP) and Weyerhaeuser Company) agreed to share their existing permanent plot growth data on managed stands with one another. Using a modification of the COSMADS (Committee on Standards of Measure and Data Sharing (Reimer, 1977)) standardized format, each institution forwarded their data to Weyerhaeuser Company who in turn organized the compilation, checked for gross errors and distributed the combined data set. This project was conceived, planned, executed, and completed in just nine months, due in a large part to the dedication of each of the participants, and to the existence of the COSMADS protocol.

STRUCTURE

The compilation included data from 6208 measurements on 1298 permanent plots at 158 installations, and produced 4874 individual growth periods. By number of plots, 37 percent had one or more thinnings, 23 percent were fertilized only, and 14 percent were both thinned and fertilized. The remaining 26 percent were neither thinned nor fertilized, and represented the "control" plots from the various fertilization and thinning experiments. No attempt was made to include the large volume of "unmanaged" natural stand data which was collected largely from temporary plots.

STRENGTHS/WEAKNESSES

If there is "strength in numbers" then this is a strong data set--both in quantity and overall quality. It is safe to say that the amount of high quality permanent plot data for this species came as more than a mild surprise to most all of the project participants. On the other hand, data compiled from a number of organizations, each with differing missions, management objectives, forestry practices, and mensurational techniques is not without its weaknesses and challenges. We consider weaknesses to be "problems", whose near-term solution is beyond our control. Challenges, however, are "problems" for which there are numerous near-term technical or subjective "fix-ups". Weaknesses and challenges can be reduced or eliminated by thoughtful planning and execution of future field studies.

Many of the weaknesses in this data set are associated with its spatial and temporal characteristics, although differing measurement protocols are responsible for several challenges. Because the data came from independent organizations whose early efforts were generally uncoordinated with one another, the geographical distribution of installations by physiographic region, age, site index, and stand density is not balanced. Current cooperative research efforts by the Stand Management Coop (Chappell, et al., 1987; Hyink, 1987) will largely eliminate this weakness in the future. Another weakness common to most permanent plot data is that there are effectively no plots with long-

term observations (25+ years), particularly those representing stands grown from wide early/initial spacings. Furthermore, the long-term usefulness of most of the plots is limited by their small size. In addition, less than 2 percent of the data are from plantations. These concerns reflect the fact that most plots came from experiments in older existing stands that were designed to test specific treatment hypotheses rather than to define response surfaces.

Challenge: Consistent Height-Dbh Curves

In sampling heights, various combinations of the following were employed across repeated measurements on a plot: (1) 100 percent of heights measured, (2) no heights measured, (3) one or two heights measured (usually tarif trees), (4) more than two but less than all heights measured (sample usually skewed toward taller trees). The problem: height-dbh curves derived independently from remeasurements with two or more sample heights would exhibit "abiological crossing" (particularly at larger diameters) through time, as depicted in Figure 1-a. Since temporally consistent height-dbh curves were very critical to our modelling efforts, the challenge was to produce such curves while eliminating (rejecting as unusable) as little data as possible. Our solution involved estimating the coefficients of all height-dbh curves on a plot simultaneously. More specifically, we estimated the coefficients of the following equation:

$$H_{ij} = 4.5 + a_j*EXP(-b_j/D_{ij}), \quad i=1,...,n_j, \ j=1,...,m \qquad (1)$$

where H is total tree height, D is tree diameter at breast height, a_j and b_j are equation coefficients for the jth measurement, n_j is the number of sample trees measured during the jth measurement and m is the number of measurements. Coefficients of equation (1) were fitted subject to: (1) the asymptote (a_j) being monotonic non-decreasing through time (i.e., $a_1 \leq a_2 \leq ... \leq a_m$), and (2) the height-dbh curves not crossing above the quadratic mean dbh (DQ) [i.e., $h_i(DQ_{i+1}) \leq h_{i+1}(DQ_{i+1})$]. Estimates of the coefficients were obtained using a sequential simplex algorithm (Olsson, 1974) based on the method of Nelder and Mead (1965). This algorithm is very robust--converging slowly but almost surely. Fortunately this procedure needed to be applied only once, since it required nearly eight hours of VAX 8600 CPU time for coefficient estimation on the 1298 plots. We believe that the efficiency could be markedly improved should we decide to make this algorithm part of a production system. Figure 1-b depicts the set of curves shown in Figure 1-a after simultaneous estimation.

For cases in which a measurement (*) with no sample heights was bounded on both sides by a measurement with a satisfactory height-dbh curve, we derived a curve in which (1) the asymptote (a_*) was determined by linearly interpolating the two a_j-coefficients as a function of age of measurement, (2) determining $h(DQ_*)$ by linear interpolation of the $h(DQ_j)$ as a function of DQ_j at each measurement, and (3) using $h(DQ_*)$ and a_* to solve for b_*.

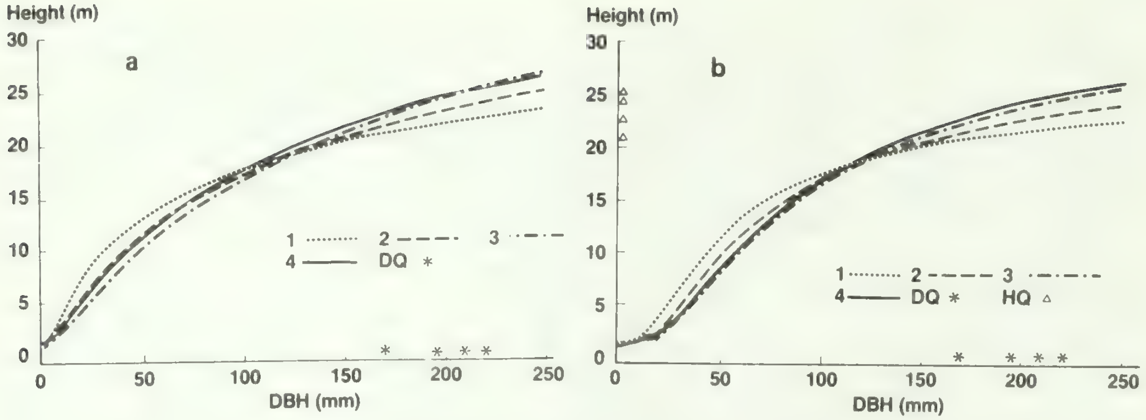

Figure 1. Successive height-dbh curves for a permanent plot (a) before and (b) after simultaneous estimation.

Challenge: Ingrowth

Western hemlock is the climatic climax species throughout Western Washington, Oregon and much of British Columbia at elevations below 2500 feet. The combination of shade tolerance coupled with abundant regular seed production results in a high rate of seedling establishment beneath existing canopies except on extremely xeric or hydric sites. Upon examining the magnitude and duration of this "seeding-in" we concluded that the ingrowth component could not be ignored in the construction of the model, particularly since realistic yield forecasts for unthinned stands were desired.

Differences in mensurational protocols between cooperators posed several difficulties in assembling a data set from which ingrowth attributes could be estimated. First, the minimum dbh measured ranged from 0.1 to 3.5 inches. Second, the policy on measuring and recording ingrowth was usually unclear and also varied by organization. Of particular consequence to ingrowth estimation (in addition to the minimum dbh measured) was the timing of the measurement. For instance, it was not always the case that ingrowth was recorded and measured at the remeasurement nearest to when it crossed a particular organization's minimum dbh threshold. Furthermore, the lack of recorded ingrowth on a plot could not necessarily be taken to mean that none existed (although we had to make that assumption to proceed).

After field examinations, discussions with Company foresters, and considering model requirements, our solution was to use only plots in which ingrowth across a 1.5-inch dbh threshold could be estimated. In addition, it was observed that virtually no ingrowth occurred in stands whose dominant height exceeded 65 feet, and, at that point, growth rates of ingrowth trees were negligible. Stand tables however were unimodal, and in spite of the age range, many younger trees were part of the merchantable stand. In thinned stands, the number of ingrowth stems observed was inversely related to the post-thinning stand density. However, few of the stems exceeded the 1.5-inch dbh threshold (probably because the thinned plots had relatively short post-thinning observation periods). More importantly (especially since we model unimodal stand

tables), we concluded that the observed ingrowth component would almost never significantly influence the post-thinning stand as far as merchantability and competition were concerned. Thus, we chose to ignore ingrowth on unthinned plots when dominant height exceeded 65 feet, and on all thinned plots.

THE MODEL

ARCHITECTURE

The class of models contained in Weyerhaeuser's "Single Acre Planning Systems" (Depta, 1984) can be generally thought of as a "hybrid" composed of a whole-stand model (Munro, 1974) with stand and stock tables generated via parameter recovery (Hyink, 1980; Hyink and Moser, 1983) described by Depta (1974). A very simplified schematic of the general model architecture is depicted in Figure 2.

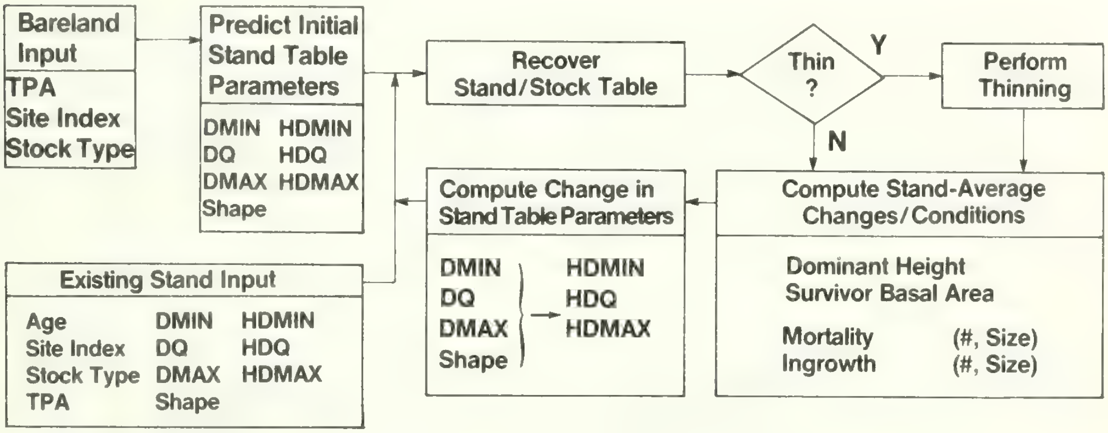

Figure 2. Schematic of general model architecture.

It is convenient to consider that any stand and stock table is completely specified by a vector of eight parameters consisting of minimum, quadratic, and maximum dbh (DMIN, DQ, DMAX), a shape parameter (or DMODE), trees per acre (TPA), and the average heights for the dbh parameters (HDMIN, HDQ, HDMAX) (Depta, 1974 1978). After characterizing the initial stand and stock table by predicting the parameters (BARELAND Input) or by inputting them directly (EXISTING STAND Input), one may view the model as ultimately "updating" these parameters by predicting biological changes and by performing thinnings. It is our (scientifically unsubstantiated) opinion that the "biological" facets of growth modelling receive an inordinate amount of attention relative to "performing thinnings". Yet, within this architecture, the thinning algorithm is inextricably linked to the "predictive" equations in all simulations of thinned growth. Thus, its mathematical properties, behavior, consistency and compatibility with the system of equations that predict biological changes can be as important to reliable yield estimation as having a sound biomathematical structure embodied in the system of prediction equations.

SELECTED COMPONENTS

Mortality

In constructing growth models for managed stands we attempt to embody three general concepts: (1) the relationship of site index, age and dominant height, (2) some generalization of Langsaeter's (1941) growth versus growing stock relationship (Smith, 1962), and (3) the -3/2 power law of self-thinning. In deriving the mortality model, we chose to use Reineke's (1933) Stand Density Index (SDI), primarily because it was analytically consistent with our model architecture in which survivor basal area growth is a prime driving variable. Two recent articles by Weller (1987) and Zeide (1987) provide comprehensive reviews of the large volume of literature on this subject.

Figure 3 depicts the Reineke relationship of DQ and TPA for the western hemlock data. The maximum stocking line (with slope of -1.605) is positioned at an SDI of 850. There has been speculation that slopes of -3/2 or -1.605 are not appropriate for some species, particularly at "lower" TPA. Examination of the individual measurements plotted in Figure 3a (which are analogous to similar depictions of data from temporary plots) might suggest this. Figure 3b however depicts the temporal character of this relationship by connecting each measurement on a plot by a solid line. Several points are worth noting.

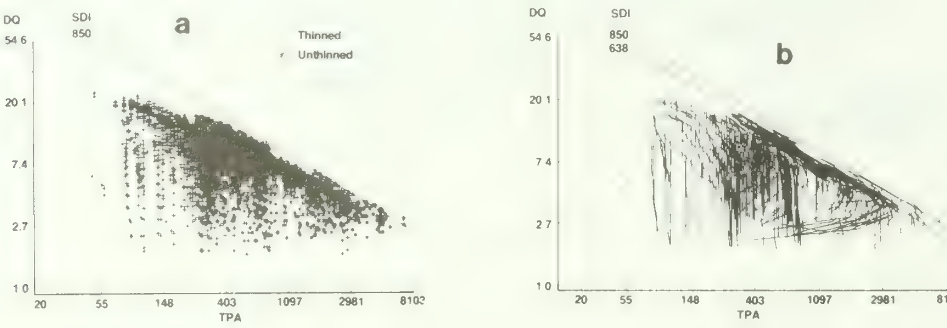

Figure 3. Relationship of DQ and TPA (logarithmic scale): (a) for individual measurements, and (b) by plot, with individual measurements connected by line segments.

First, lines running in a northeasterly direction represent plots with recorded ingrowth. Second, the lower stocking line depicts an SDI of 639 (75 percent of the maximum - Relative Density (RD) = 0.75). This was chosen to represent an "asymptotic-average maximum density line -- a line which the "average stand" might follow during self-thinning. Third, stands in the vicinity of this line are represented by lines running in a northwesterly direction, and their slope appears to be adequately approximated by -1.605. Fourth, stands represented by lines at TPA less than 300 come almost exclusively from thinned stands (depicted by + in Figure 3a). Plots exhibiting steep northwesterly slopes at low to moderate relative densities (RD) generally reflect mortality associated with "thinning damage" (particularly on small plots) rather than some "competition-induced" phenomenon.

The geometry of the Reineke size-density relationship is shown in Figure 4. As depicted in Figure 3b, elements of the <u>surviving</u> stand (DQ and TPA) define a straight line segment (virtually always) running in a north to northwesterly direction (line h) during a single growth period, generating an angle of deflection (M). This angle (M) will be zero if no mortality occurs, and will equal ARCTAN(1.605) if exactly following some Reineke maximum stocking line.

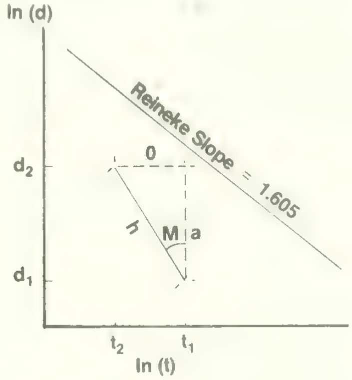

Figure 4. Geometry of Reineke (1933) size-density relationship.

Now, in deriving a mortality model, survivor basal area growth (dBAs) is

$$dBAs = k(T_2*D_2^2 - T_1*D_1^2 + T_d*D_d^2) \qquad (2)$$

where T_2 is the number of initial trees per acre (T_1) surviving, D_i is quadratic mean dbh of the T_i, i=1,2, T_d is the number of periodic dead trees (i.e., T_1-T_2), D_d is the quadratic mean dbh of the T_d, and k is a constant which converts diameter to basal area per unit area. Given

$$TAN(M) = -ln(T_2/T_1)/ln(D_2/D_1), \text{ and subsequently}$$

$$D_2/D_1 = (1-T_d/T_1)**(-1/TAN(M)), \text{ equation (2) may be rewritten as}$$

$$(1-T_d/T_1)^{(1-2/TAN(M))} = 1 + dBAs/(k*T_1*D_1^2) - (T_d*D_d^2)/(T_1*D_1^2) \qquad (3)$$

Solution of this transcendental equation is accomplished by approximating the left-hand-side with the first three terms of a Maclaurin series of the form

$$(1-x)^a = 1 - ax + (1/2)(a)(a-1)x^2$$

where a = (1-2/TAN(M)) and x = T_d/T_1, and solving the quadratic equation

$$(1/2)a(-2/TAN(M))x^2 + ((D_d^2/D_1^2) - a)x - dBAs/(k*T_1*D_1^2) = 0 \qquad (4)$$

for T_d by obtaining the positive root, given D_1, T_1, dBAs, M, and D_d.

Since D_1, T_1, and dBAs exist either as initial conditions or as a prediction from the survivor basal area growth model, we must find M and D_d in order to obtain an estimate of T_d. A similar derivation using a volume-based density index is given by Flewelling (1981).

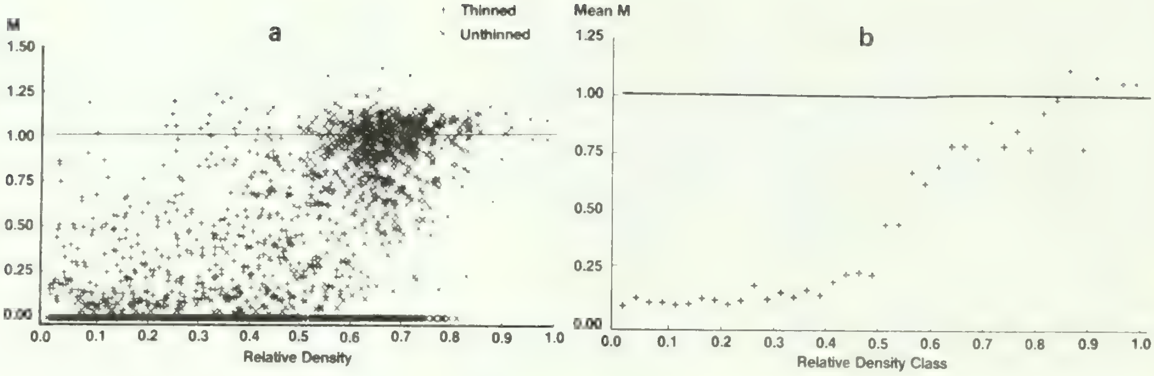

Figure 5. Relationship of angle (M) (radians) and relative density (RD) for (a) individual growth periods and (b) population means by 0.025 unit classes of RD.

Figure 5a depicts the relationship between and angle of deflection (M) (radians) and relative density (RD) for all thinned (+) and unthinned (X) growth periods. The horizontal line depicts the slope of the Reineke maximum size-density line, ARCTAN(1.605). The large deflections for some thinned plots depicted in Figure 3b are seen (+) in the upper left-hand portion of Figure 5a. The plots (at higher densities) tracking parallel to the maximum stocking line in 3b are seen (X) in the upper right-hand portion of Figure 5a. While the amount of variation (noise) in the data is not unexpected, the mean trend by 0.025 unit classes of RD (Figure 5b) is quite clear and quite rational. That is to say, at low RD (0.0 to 0.4) there is a small deflection (M) which has a large "random" component (as opposed to a "competition induced" component). As RD increases, competition induced mortality increases and appears to approach a slope very similar to Reineke. The lack of data with mean M greater than 1.01 radians in Figure 5b does not present a strong argument to support a slope greater than 1.605 for the western hemlock represented by this data. Rather, it is indicative of the average trend being a gradual asymptotic approach to a line with a slope of approximately 1.605.

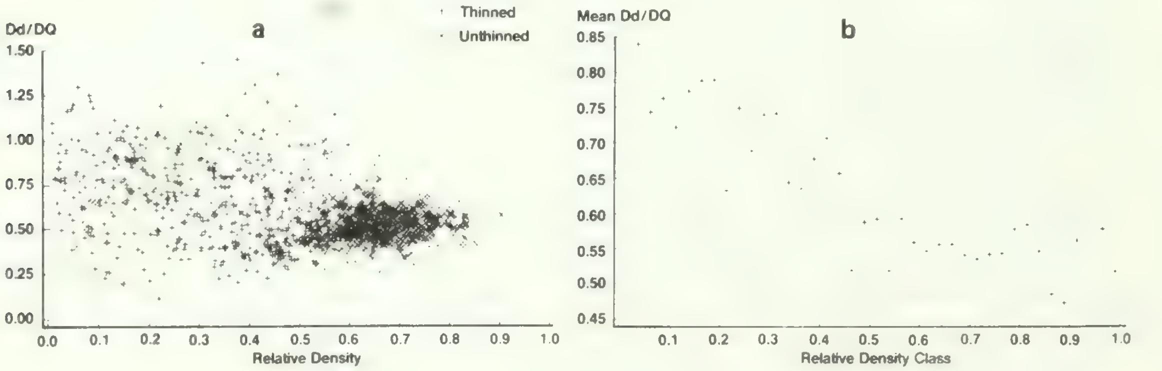

Figure 6. Relationship of Dd/DQ and relative density (RD) for (a) growth periods experiencing mortality and (b) population means by 0.025 unit classes of RD.

A convenient characterization of the average size of periodic dead trees (Dd) is the "relative size of dead trees" (Dd/DQ). The relationship of Dd/DQ and relative density (RD) is illustrated in Figure 6 for (a) individual growth periods, and (b) population means by 0.025 units of RD. As with M, the inherent variability appears quite high but the mean trend seems quite clear and rational. At low RD where the "random" mortality component is large relative to the "competition induced" component, the average size of dead trees approaches the average size of live trees (Dd/DQ is close to 1.0). As RD (and competition) increases, the relative average size of the dead trees decreases, presumably because these trees (on average) are less able to withstand the rigors of competition.

Based on the relationships depicted in Figures 5 and 6, equations to predict M and Dd (as functions of RD) were developed, thus allowing the estimation of Td via equation (4). We feel that this approach is useful insofar as it: (1) is based upon a reasonable biological hypothesis, and, (2) has reasonable and consistent biomathematical properties that ensure reasonable extrapolations and also allow for parametric adjustment of (a) the average asymptotic stocking stocking line (intercept), and (b) the slope of that line. This formulation does not allow for any separation of the "random" and "competition induced" components of mortality (assuming they could be definitively determined), nor does it apply to individual trees.

Consistent Height Predictions

Although models of this architecture deal primarily with "stand-averages" rather than with attributes of individual trees, certain compatibilities and consistencies must be present when stand tables are "recovered" to produce means by dbh class. One such compatibility involves maintaining consistency between dominant height (Hd) as an attribute of the whole-stand model and the Hd embodied by the average height by dbh class in the stock table.

Historically, the research and inventory definitions of dominant height have differed. We approached this dilemma by defining a dominant height that could be used by research and inventory alike. Hence, we define dominant height (Hd) to be the average height of the 80 largest trees per acre (by dbh) as sampled from the 4 largest trees (by dbh) from an appropriate number of 1/20 acre plots. We like this definition because it is objective rather than subjective. Besides having a clear analytical definition, its sampling definition helps insure consistent and reproducible estimates of Hd. Within this definition, dominant dbh (DHd) is

$$DHd = \left(\sum_{i=1}^{80} Dbh_i \right)/80,$$ and Hd may be estimated by equation (3) as

$$Hd = \left(\sum_{i=1}^{80} (4.5 - A*EXP(-B/dbh_i)) \right)/80. \qquad (5)$$

To guarantee compatibility of Hd between the whole-stand model (where Hd is known), the recovered stand table, and the (yet to be computed) stock table, equation (5) is rearranged to give the asymptotic height parameter (A) as a function of Hd, the shape parameter (B), and the vector of the 80 largest dbh's,

$$A = 80*(Hd - 4.5) / \left(\sum_{i=1}^{80} EXP(-B/Dbh_i) \right).$$

The shape parameter (B) is predicted as a function of attributes (known to the model) such as Hd and DHd. Thus, using the recovered stand table to estimate DHd, the shape parameter (B) is predicted, and the asymptotic height parameter (A) determined, such that the Hd computed in equation (4) is the same as that predicted from the whole-stand model.

Thinning Algorithm Considerations

In models of this architecture, the thinning algorithm's function is to turn one continuous unimodal diameter and height distribution into another. Accomplishing this task in a biologically and operationally consistent manner is key to growth projection in thinned stands, particularly since the <u>after thinning</u> stand and stock table defines the "initial conditions" to be grown forward. In our model, thinnings (at any time) are specified by the ratio of the quadratic mean dbh of the <u>cut</u> trees to the quadratic mean dbh of the trees in the stand <u>before</u> thinning (d/D), and some measure (number or proportion) of the trees or basal area per unit area to be removed (or left). These parameters mathematically specify two of the algorithm's constraints (the DQ and TPA <u>after</u> thinning). Unless the underlying distribution/density function is characterized by only one parameter, additional constraints must be imposed for each remaining distribution parameter.

In our model, there are three such parameters: DMIN, DMAX and the shape-parameter. Specifying the <u>after-thinning</u> DMIN and DMAX is relatively straightforward. The shape-parameter is then left with the responsibility of characterizing an after-thinning stand table that is both rational with respect to the type of thinning emulated <u>and</u> consistent with the before-thinning stand table. At least one constraint on the shape parameter (or on the set of parameters for that matter) is required to prevent <u>ghosting</u>. <u>Ghosting</u> is the "creation" of trees as a result of improperly turning one diameter and height distribution into another, and is depicted in Figure 7.

Figure 7a depicts a properly executed thinning. Note that "ghost" trees appear in the largest three dbh classes in 7b insofar as they did not exist in the before-thinning stand table in 7a. There are any number of other "loose" constraints on the shape-parameter that may be required to meet other considerations imposed by thinning methods, say. Sometimes, thinnings with requested d/D and after-thinning TPA cannot be accomplished.

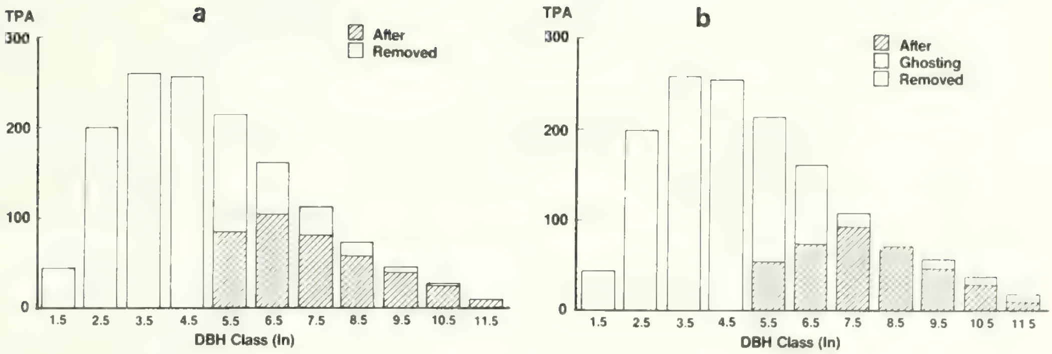

Figure 7. Examples of (a) proper thinning simulation and (b) ghosting.

Another form of ghosting that is theoretically possible (although we have never observed it) manifests itself in successive stand and stock tables whereby trees are "created" in the smaller diameter classes (actually stolen from the larger dbh classes) in periods in which no periodic ingrowth is predicted.

CONCLUDING COMMENTS

We have enjoyed the opportunity to share some of our experiences in developing a managed stand growth model for western hemlock. To everyone who has spent the bulk of their career modelling even-aged monocultures of intolerant conifers, we recommend (as mentally challenging and spiritually rewarding) a diversion into the world of predicting growth and development for tolerant conifers. For those of you brave(?) enough to take on modelling of mixed-age, mixed-species stands of indeterminate tolerance, we offer our sympathy.

We cannot stress strongly enough our belief that cooperative research efforts will be at the root of many exciting future research advances. Our efforts chronicled herein would not have been possible without such activity. For those of you using (or considering using) model architectures similar to ours, we have attempted to highlight several concepts that we have found to be both timely and relevant. We hope that you will find them useful as well.

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SOME FACTORS THAT WILL AFFECT THE NEXT GENERATION OF FOREST GROWTH MODELS

Rolfe A. Leary[1]

ABSTRACT. Several types of factors will affect the form and referents of future growth models; these include philosophical, scientific, technological, educational, and organizational factors. Philosophical factors are characteristics of questions and answers in a science as it matures. Scientific factors are summarized in current and likely future components of growth modelling paradigms. The primary technological factor is the relation between costs of computer hardware and field measurements. Educational factors relate to balance between formal and factual science graduate education tracks. Organizational factors deal with the problem created by too few scientists in too many places with too little money, institutional reward styles, and procurement policies of large users.

INTRODUCTION

What will the growth models of the future be like? How will they differ from those of the present and recent past? I will outline some of the factors here that I feel will be important. By "affect" in the paper's title, I mean alter the means and methods by which growth models are constructed, and the kinds of tree assemblages to which the models refer. By "generation", I mean something similar to Moser's (1980) "historical chapters". Many factors will be important, so I focus my discussion on five broad categories: philosophical, scientific, technological, educational, and organizational. Under each, I highlight some important trends and speculate how each might be important.

Moser (1980) suggested the following historical chapters in the development of growth and yield models: a) yield tables (normal, variable density), b) yield functions, c) compatible growth and yield models (even-aged case, uneven-aged case, systems of differential or difference equations), d) diameter distribution approaches, e) simulation approaches (distant-independent stand models, distant-dependent individual tree models, distant-independent individual tree models). These chapters are a mixture of categories that describe how scientists have represented forests and what the models refer to. Here I assume that we wish, ultimately, to make a statement about a stand.

FACTOR CATEGORIES

The era when a scientist could initiate and complete a long-term study of a species or forest type is ending, if not over. Scientists who study

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forest dynamics are being affected by many of the same factors affecting scientists in other disciplines. These external (philosophical, technological and organizational) factors will certainly have a significant influence on what growth models look like in the future. In addition, factors internal to our own subdiscipline (scientific and educational) as well as neighboring disciplines will weigh heavily on future model form and referents.

PHILOSOPHICAL

Although little discussed, philosophical factors will play a large role. By discussing them here, I hope their role can be more explicitly examined. These factors come from two subareas of philosophy: 1) philosophy of science and 2) ontology. Philosophy of science takes up questions such as how sciences change as they mature. What is the primary goal of science (prediction or explanation)? What constitutes an explanation? Ontology is concerned with how we as scientists organize and categorize reality. Of concern to ontologists are such basic notions as system, level, hierarchy, change, interaction, and possibility. Systems science is a discipline with a particular ontological perspective. The following discussion is centered on the question of science maturity with support from the ontology of systems.

Maturation of science

Nonlinear algebraic equations as growth models date to the 1930's in the United States (Moser 1980), putting us 50 years into the task. Are we headed in a reasonable direction? Are we producing knowledge? As rapidly as possible? What are appropriate evaluation criteria? Philosophers and scientists have assembled three criteria to assess science maturity: breadth (it covers the range of phenomena studied in the science), depth (it uses more than one level of biological and/or physical organization in its constructs), and cogency (forcible, clear, or incisive presentation) (Bunge 1968). The notions of depth and breadth relate directly to those of questions and answers.

Questions

Scientists are considered expert question answerers. But, scientists specialize only in certain kinds of questions. Formal sciences such as mathematics, and to some extent statistics, help to answer methodological questions (How to?). Factual scientists (of concern here) specialize in making statements about nature, hence they answer the following questions:

What is the character of? (The answer is called a description.)
What if? (The answer is called a prediction.)
Why? (The answer is called an explanation.)

Each kind of question can be further subdivided. (For example, "What if?" questions can be broken down further by answer source: prophecy, guess, prognosis, statistical prediction, scientific prediction.) The important point is, within a specific problem area, questions are not of the same difficulty to answer. Typically, "What is the character of?" questions can be answered most easily. "What if?" questions, with the possible exception of full scientific prediction based on law-like relations, are more easily answered than "Why?" questions. Answers to "Why?" questions typically, though not exclusively, result from analysis (reductionism). In analysis, the object of study, the stand, tree, stem,

crown, leaf, etc., is treated as a system with various subsystems. In turn each subsystem can be broken into its component subsubsystems (e.g., crown into branches and leaves; stem into heartwood and sapwood). Further, each referent (e.g., leaf, sapwood) has a large number of properties that could be studied. The detailed workings of each major level, when conjoined with the physical, chemical, energy, and biotic environment are extremely complex.

In traditional growth prediction, we often (perhaps, too often) try to distill the mechanisms at work in only one or two of the biological levels, incorporate what we can from the physical level, and express the interactions and interdependencies using a single mathematical equation. Process models, such as developed by ecophysiologists, on the other hand, work at very basic levels and sum/integrate results to higher levels of organization. Perhaps ecophysiologists are the scientists we should expect to provide functional explanations of, for example, carbon allocation to stem increment and other important "Why?" questions.

Those modelling at lower (more aggregate) resolution levels would do well to select equations having a theoretical basis and having interpretable numerical constants, as well as goodness of fit (Bunge 1967). Of course, not all system properties can be included in low resolution models, but what is left out will still appear--as errors of the estimates of equation parameters. By comparing predictive power of functional explanatory models and traditional predictive equations, it will be possible to assess the "costs" of leaving out one or more levels. In sum, being able to answer "Why?" questions only comes with understanding of the phenomenon, hence is more difficult than "What if?" or "What is the character of?" questions.

Answers

I will limit my consideration here to answers that are declarative statements about reality, i.e., factual rather than formal (methodological) propositions. Answers may be categorized in a number of ways, but I focus on generality of object classes. A singular statement contains or implies "...in one case...", an existential statement contains or implies "...in one or more cases...", a bounded universal statement contains or implies "...in all cases in universe U_i", while a universal statement contains or implies "...in all cases...". Assuming equal accuracy among answers, science puts a high premium on general ones.

The universe about which answers are desired is large. It must include subject tree species in a specified range of moisture, nutrient, heat and light regimes, and biosocial environments. We begin to see this by cross-tabulating the species, age, and site conditions of stands in a geographical region. This three-dimensional cube has cells for pure even-aged stands as well as for many species and ages together.

It is difficult to make very general statements without the aid of a mathematical equation. Use of an equation introduces another level of possible generality. As we seek ways to mathematically express our deep understanding of each kind of stand, we may wish to use the kind of mathematics that has representation power to handle the most complex stand (many species of differing ages on different sites). We can have generality of the governing equation and/or generality of the solution to that equation given certain initial conditions. When a science has general

equations that apply to a very large number of the circumstances under study (the numerical constants and initial conditions may not be generally applicable), we may say that it has breadth (Shive and Weber 1982).

Question difficulty and answer generality are interdependent, so it makes sense to combine them into a two-dimensional framework (Figure 1). The framework makes it possible to locate disciplinary frontiers and to map one's work relative to them. Further, it helps to see if one's direction of change is what is typical of successful science and scientists.

QUESTION (DEPTH)

	WHAT CHARACTER?	WHAT IF?				WHY?
			PREDICTION			
ANSWER	DESCRIPTION	. .	PROG.	STAT.	SCI.	EXPLANATION
IN ONE CASE						
IN ONE OR MORE CASES						
IN ALL CASES IN U_i						
IN ALL CASES						

Figure 1. Framework formed by interrelating question difficulty (depth) and answer generality (breadth) (Leary 1985).

A maturing science changes in the type of questions asked (moves toward the right) and in the generality of answers given (moves downward). But, to move in either direction, one must overcome obstacles. To move to the right stretches scientist's disciplinary training, so they must learn a new discipline or join with colleagues expert in the needed fields to form interdisciplinary research groups.

Movement down the framework may require that we understand why trees grow as they do in pure stands before we can understand their growth in mixtures, on a variety of sites, and when tree ages are different. (Where would we be in our understanding of the abiotic world of mostly mixtures if chemists had not determined the properties of constituent elements in their pure state?) We have fair predictive power down to the bounded universal level for a number of species in the pure stand condition. But the i in U_i is at least 15 just in the North Central region of the United States.

Modellers must constantly re-evaluate the methods used to express models. Even though current efforts may be directed at the pure even-aged stand, we should view that as the first step toward representing the mostly mixtures real world, and pick our modelling methodology accordingly. Systems of first order differential or difference equations have become a widely used method with the advent of individual tree models. Systems of integro-differential and second order differential or difference equations may be the future method of choice because they offer a better opportunity to incorporate knowledge

developed by ecophysioiologists into predictive equations and they can be localized more easily (Hamlin and Leary 1987a,b; Leary and Hamlin 1987).

Let's leave the philosopher's criteria at that. The criteria offer scientists a compass when examining a direction to head. Movement to the right seems assured. Movement downward is more problematic. What is required appears to be a combination of well-conceived, systematic research programs (Leary 1986) and the use of appropriate higher order mathematical equations.

SCIENTIFIC

The scientific aspect of growth model prediction systems has many dimensions. Instead of trying to go into each, I summarize them using the concept of paradigm (Kuhn 1970). A paradigm is a shared belief among a large and often powerful number of scientists about how some aspect of the world works, or how it should be studied. In a sense, a paradigm is a stereotype -- a simple handle by which a body of thought can be grabbed and discussed. Is there a current paradigm? If so, what is it? Let me first attempt to capsualize my thoughts on the current paradigm, and then suggest some probable characteristics of the next paradigm.

Current Paradigm

The recent past/current paradigm can be succinctly expressed by grouping the beliefs by important categories:

Environmental factors
- are satisfactorily summarized in site index, which is constant
- climate is assumed constant

Model expression
- a single nonlinear algebraic or first order functional equation fit by nonlinear regression methods

Model selection criterion
- much emphasis on goodness of fit of model to data

Research method
- no more than one (if one) hypothesis is formed,
- confirmation is often attempted,
- little distinction is made between the discovery and justification phases of science

Primary hypothesis
- stand property (average diameter, basal area, etc.) - time relation

Emerging Paradigm

What is "emerging" is not the paradigm, but the pieces that, fit together, may constitute the next paradigm. I discuss them briefly under the same headings as above, but order them by my estimate of how soon they may become part of the next paradigm.

Primary hypothesis
- property-property relations

  Increasingly, models start from property interdependence (competition-density, self-thinning rules, height-diameter, etc.) and infer property time series. The Bakuzis yield matrix in Figure 2 illustrates the difference in approaches. Property interdependence has limited to pure even-aged stands, however.

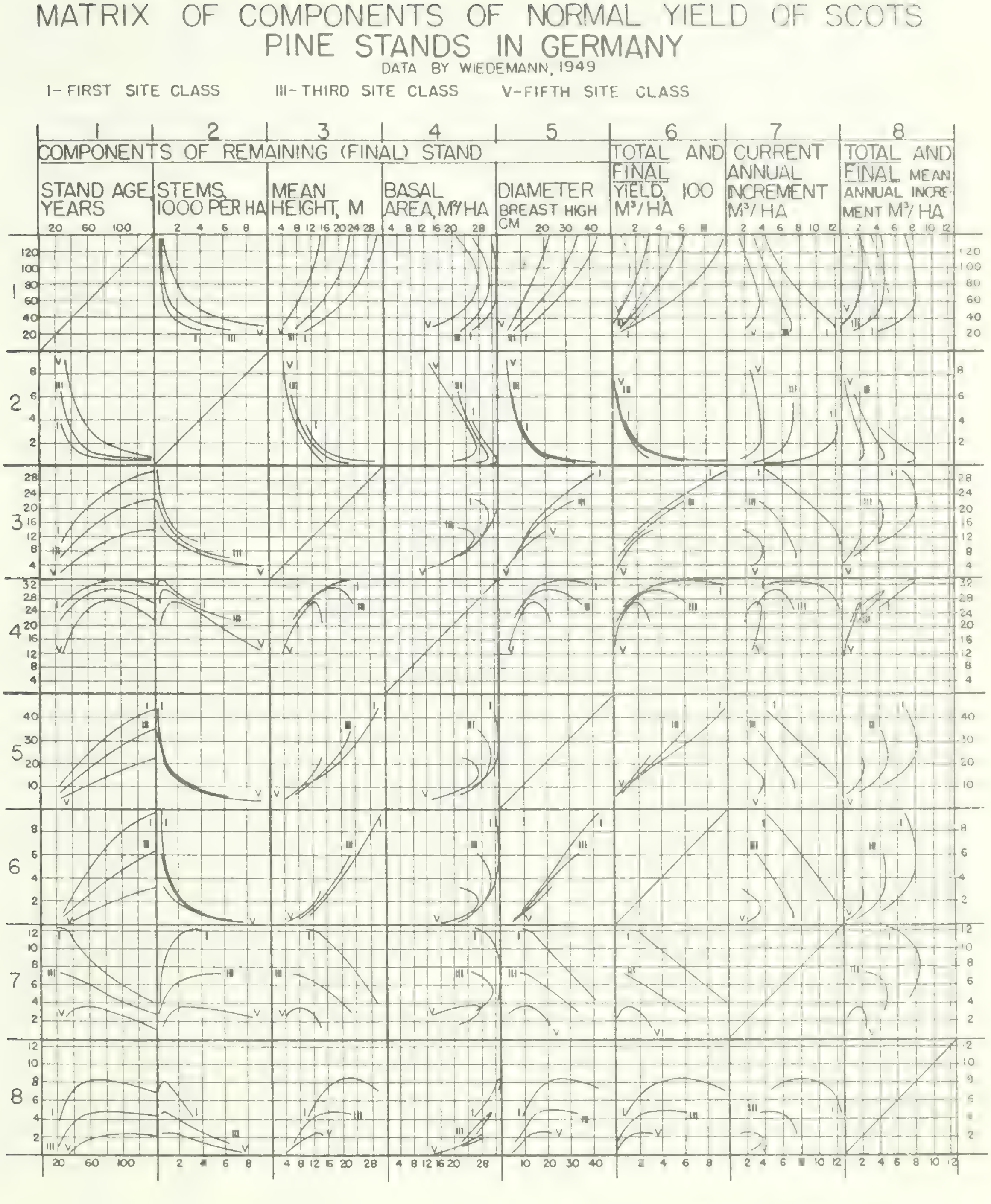

Figure 2. Matrix of yield table components for Wiedemann's Scots pine yield table. Matrix was conceived by E. V. Bakuzis in 1969 and hand drawn shortly thereafter (Bakuzis 1969, 1976). Column 1 shows traditional stand property-time relations. Cells below row 1 and to the right of column 1 show property-property relations, e.g., cell (2,5) is Reineke's rule, (6,3) is Eichhorn's rule, etc.. Traditionally the primary hypothesis of growth models has been a column 1 relation. Two column 1 hypotheses (models) can be used to deduce a property-property relation. Recently, one or more property-property relations have been used to form the primary hypotheses, and property-time relations have been deduced from them.

Environmental factors

- Site index is in a crisis (epicycles of anamorphic, polymorphic, non-disjoint polymorphic) phase. It will be replaced by physical, chemical, and physiographic factors of the site.

Model^ expression

- Single and systems of linear higher order equations (integro-differential, and second order) will likely replace the single nonlinear algebraic equation.

Model selection criteria

- Emphasis on interpretability of equation numerical constants will probably not be possible until higher order functional equations ease the goodness of fit burden.

Dominant research methodology

- The emphasis on confirmation is unlikely to be replaced soon.

Some items in the list have a distinct even-aged, mono-specific, stand bias. That is partly because most current research is being directed at those kinds of forests. Others will apply equally well in uneven-aged stands and multi-species stands. Generality of our findings commands that they do.

TECHNOLOGICAL

Anyone who develops mathematical models must be aware of the rapid advances in computer hardware and software, especially the ease of use provided by desktop machines. More dramatic advances are promised from parallel computer architectures and the operating systems to exploit them. At the same time dollars available to measure the crowns, roots, and stems are steadily decreasing. While laboratory instruments can be connected to micro-computers for automated data acquisition, field data collection has progressed much more slowly in this direction. In sum, an acute imbalance is developing between the power to compute and the money to measure. Figure 3 summarizes the relative changes in costs to compute and costs to measure since the mid 1970s.

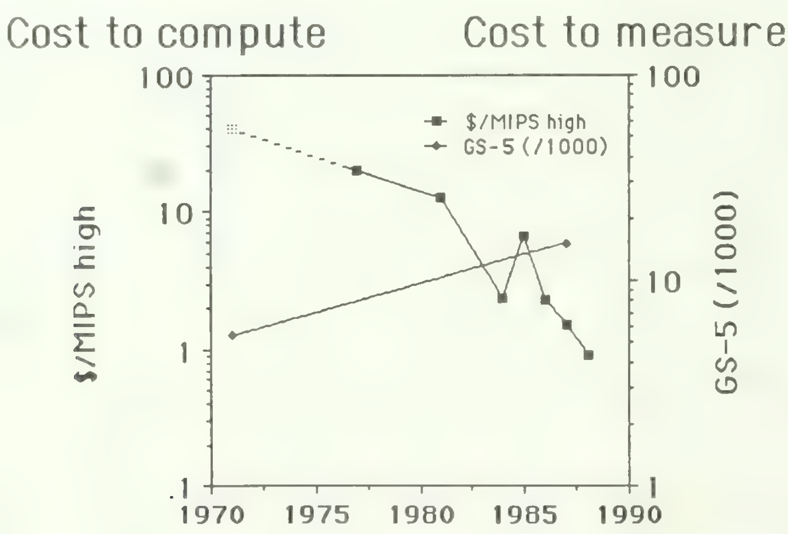

Figure 3. Changes in microcomputer cost for a million instruction per second performance rate and the salary of a GS-5 technician to do measurements (primary data source Crecine 1986).

It was only a decade or two ago that the imbalance was reversed. During that era, file drawers were filled with field sheets completed by highly skilled but modestly paid technicians. The current imbalance will likely increase "strapping", a generic term that includes boot strapping, i.e., the creation of 'data' by permuting a limited number of observations so as to give a data set the appearance of a different set of measurements. A danger is developing that future models will be constructed on the basis of few measurements. Measurements are not required in the discovery phase of science, but they are in the justification phase.

However, one can argue that growth modelling has suffered from the existence of too much data. And, of the wrong kind. Action, data analysis, has too often preceded thought. Analysis has been constrained by what could be done with available data, not what needed to be done. In addition to having too much data, one could argue that much of the data was for the wrong conditions -- too much in the middle range of predictor variables, and not enough at the boundaries.

Computer technology can also help organize, store, retrieve, and deliver knowledge about trees and forests. Knowledge organization systems built around computers could well have a greater influence on future growth models than the computer's vaunted ability to do numerical computations.

EDUCATIONAL

Where will future growth models originate? In the dissertations of graduate students? Or will they rise from the ashes of experienced scientist burned by the inadequacies of previous models? In either case, the educational emphasis of current graduate students will be important. Past decades have seen advances on a number of fronts that should be of value to us: plant population biology, ecophysiology, soil science, forest meteorology, to name four. What is now available is a substantial body of experience, observation, conjecture, test and theory in several factual science areas that will substantially deepen our understanding of forest dynamics. This factual science alternative emphasis has long been needed by those interested in a research and teaching career in forest growth and yield. Traditionally, the emphasis has been almost entirely a formal science one -- statistical theory and methods in various forms and flavors. Needed also is an alternative formal science track emphasizing the biomathematics of developing predictive equations. Any group that focuses too much on a single class of referents (e.g., pure even-aged stands) using a single methodology (e.g., univariate nonlinear regression) is vulnerable in an era of competitive research funding. We are, after all, in the business of making predictive statements about nature, and we should change as needed to make our statements deeper and more general.

ORGANIZATIONAL

Perhaps the most important factors will be the organizational ones: critical mass of scientific talent, fragmented responsibilities, user influences, and institutional reward style. The current talent situation is, briefly stated, too few people in too many places with too little money. We have been in an era of 'free enterprise', of 'doing our own thing', in growth modelling. As our science matures and moves toward breadth (generality) and depth (explanation), the critical mass of ideas, technical expertise, and funds increases dramatically. In the future

there will likely be just a few organizations that can (and choose) to provide the required support. We can expect to see consortia, cooperatives, and other alliances formed as this trend continues.

The organization of research has in some cases made it difficult to get generality. For example, at one count there were about 15 separate research work units responsible for growth and yield of tree species in the eastern United States (Leary 1985). The same funds and scientific talent may have produced more new knowledge if combined in fewer but larger efforts.

The users of growth and yield research results could greatly affect what we do if they used a "procurement" approach similar to the USDA Forest Service's approach in selecting a provider for its computer hardware. Model performance criteria would be established, model construction funds would be awarded to serious bidders, and the winning model would be selected in a test of model performance against a closely guarded data set.

The reward style of research institutions will also affect the form of future growth models. Moving the frontiers of knowledge about a tree species or stand to the right and/or downward in Figure 1 requires risking failure. Research organizations can encourage the necessary risk-taking by: 1) recognizing question difficulty and answer generality in productivity assessments and 2) making clear its reward style, s, in the formula

$$(\text{reward}) \propto ((\text{question difficulty}) \times (\text{answer generality}))^{s} ,$$

(Leary 1985). Organizations with reward styles near 0 will likely get lots of singular descriptions, while those with styles near 1 will encourage risk of failure in seeking universal explanations.

DISCUSSION

In sum, scientists can control some of the factors, simply use some, and only react to others. It makes sense to focus one's energies on those factors we can control. Organizational factors are typically beyond the control of the individual scientist, hence one is left to react to organizational dynamics. Technological factors, especially those dealing with micro-computers, are also typically beyond the control of the individual scientist. One is left to react to, and use, them. The remaining three categories of factors, philosophical, scientific, and educational, are subject to a large degree of control. However, control in the case of educational and philosophical factors is primarily personal control; one can select one's own graduate program, or change major professors if student expectations do not match institutional requirements. Further, one can to a large degree control the difficulty of the question asked, but not the generality of the answer given. The kind of control exerted by the scientific category of factors is collective, not personal. A paradigm is a shared belief among an often powerful group about how some bit of nature functions, how it is organized, or how it should be studied. Thus, the paradigm cannot be changed by one person alone.

Factors and subcategories are interdependent. Reward styles affect the kinds of questions asked. Technology, especially when it is used to

organize and deliver knowledge, can also greatly affect the depth of question asked, and the computational capabilities of computers can affect the generality of our answers. Questions asked will depend on the graduate educational program emphasis, especially the division between formal and factual sciences. Will they be deep and difficult questions, or superficial and easy? Clearly, graduate educational programs will affect the future paradigm. However, in light of Planck's principle, "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (Hull et al. 1978), the timing and direction of paradigm change are unclear.

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ESTIMATING GROWTH AND YIELD OF THINNED SLASH PINE PLANTATIONS ON OLD FIELDS

Kenneth D. Ware, Bruce E. Borders and Robert L. Bailey[1]

ABSTRACT. A compatible system of equations was developed to estimate growth and yield of old-field slash pine (Pinus elliottii Engelm.) plantations subjected either to no thinning or to various levels of thinning from below. Empirical estimates for parameters of these equations are based on the Southeastern Forest Experiment Station's Cordele slash pine plantation density study established in 1958 with a large number of industrial cooperators. The systems model includes functions derived to estimate survival, to project basal-area growth with various levels of thinning, and to provide better fitting site-index relationships. The diameter distributions were then modeled by the Weibull distribution. Extensive tests led finally to the development of percentile-based approaches for characterizing the diameter distributions on the basis of observed current stand tables and less restrictive assumptions than usual about underlying probability density distributions. This approach enables the user to apply available information about current stand structure to improve estimation and projection of future growth and yield.

Evolution of the concepts and procedures developed here for thinned plantations of slash pine is traced to the present through the synergism resulting from particular groups of scientists applying improved data bases, computational and analytical power, and conceptual tools through cycles of empirical and theoretical emphasis in the science. Using this synthesis as a basis, future modelling approaches and philosophies are discussed.

INTRODUCTION

Our objectives are, first, to report our research on growth and yield prediction systems for slash pine plantations subjected to various levels of thinning after establishment on old-field sites in the Southeastern United States, and second, to relate the development to the evolution both of information needs for predicting dynamics of such stands and the technical tools and philosophical approaches applied to such problems. These evolutionary trends have been contemporaneous and the motivation for developing new information, new concepts and new approaches is, of course, related through strong feedback mechanisms to evolving forest management technology, scientific techniques and theory, computing power and changes

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in philosophical outlook. Although this evolution is not unique to our situation, to slash pine, or to the southeastern U.S., the longevity of research and data bases on growth and yield of slash pine does give an uncommon opportunity to trace and learn from this evolution.

HISTORICAL AND TECHNICAL PERSPECTIVE

Growth and yield information for the southern pines has been regularly reviewed since 1975 through, for example, Williston's bibliography, and then Farrar's and Burkhart's reviews in 1979. A detailed review for slash pine was done by Ware, Bailey and Feduccia (1983). More recently Burkhart (1985) considered the newest developments. We have come a long way from MP-50's normal yields and Coile and Schumacher's (1964) variable-density approach for predicting growth and yield of slash pine.

In the late 1950's the evolution of technology for growth and yield prediction accelerated. F. X. Schumacher's work with applied regression analysis (so advanced for the time that he was elected a fellow of American Statistical Association) brought the technical tools for developing variable-density whole-stand yield prediction systems. These early systems were based on a rich combination of empirical data and empirical data-fitting methods, early ideas about appropriate equation forms for the components of the models, etc. Considering the lack of statistical tools and computational power, this work was not only on the cutting edge conceptually, but was prodigious labor.

Jerry Clutter, as Schumacher's student, as a supervisor at the Duke University Computing Center and as biometrician at the Southeastern Forest Experiment Station, was the man for the times--perfectly placed intellectually, geographically, and institutionally. He, Frank Bennett and associates started work on slash pine growth and yield that not only leads to what we are reporting, but has influenced much of what is reported in these proceedings (Bennett, McGee, and Clutter, 1959; Clutter and Bennett, 1965; Bennett and Clutter, 1968; Bennett, 1970.)

The use of a mathematical function or probability distribution function to characterize diameter distributions has early origins. The ancient "Law of De Liocourt" for all-aged stands was further developed by H. Arthur Meyer in the 1940's. In 1930 Walter H. Meyer published his studies on diameter distribution series in even-aged stands (Meyer, 1930). Later, he applied these ideas to loblolly pine (Meyer, 1942). Given the state-of-the-arts of statistics, of mensuration and of computing in the 1930's, it is not hyperbolic to call these works monumental. Why was it nearly 40 years before the diameter distributions approach made a comeback? Anyone who has used 1958's most efficient electric Monroe calculator to fit truncated forms of Meyer's Charlier curves and Bliss's various truncated normal and log-normal distributions will know. The senior author of the present paper has done this for much of the work reported by Bliss (1967) and Bliss and Reinker (1964). Diameter distributions were too much trouble. It had to be simpler when Sir Ronald Fisher was fitting the Poisson to the frequency of deaths by horsekick in the Prussian cavalry.

There are obvious scientific and technical reasons for evolution from whole-stand normal-stocking approach of MP-50 to the variable stand-density

approach, and then to the diameter-distribution approach. The normal-stocking concept had many shortcomings, but the graphical techniques of the day made multi-variable prediction infeasible. By the mid-1950's, graphical techniques could be discarded in favor of statistical regression procedures based on mechanical calculators. Then about 1958 came internally-stored-program electronic computers of rapidly increasing size, ease-of-use and computing capability. This stimulated new developments in statistical theory, procedures and philosophies for estimation and model building.

By the late 1960's, therefore, some were finding new feasibility for a diameter distribution approach (Clutter and Bennett, 1965). Burkhart (1971) and Bailey and Dell (1973), direct heirs to the developments described above, published on these diameter distribution approaches, including use of the Weibull.

Parallel to it all, and essential to the developments in growth and yield prediction, remeasured series of permanent plots established by scientists such as Bennett, Jones and Clutter were beginning to yield data. The Southeastern Forest Experiment Station's various stand density studies such as the one that is the basis for our work, were among the foremost. As mentioned earlier, our data base is the Cordele Slash Pine Plantation Stand Density Study established by Frank Bennett and Earle Jones of the Southeastern Forest Experiment Station in collaboration with industrial cooperators.[2] The cooperators have been listed and the data base fully described by Clutter and Jones (1980) and by Bailey, Abernethy, and Jones (1981).

COMPONENTS RELATIONSHIPS

To develop a system that had desirable characteristics for predicting growth and yield for these thinned stands we began with the usual task of developing models for changes in the input variables, measures of stand density, stocking, and site productivity. Our a priori requirement was that these relationships should, so far as possible, be mathematically compatible and consistent, should be logical in structure and results and should characterize observed effects well. Substantial individual studies were carried out to determine how well the Weibull probability density function really did characterize the diameter distributions of these thinned stands, to develop improved models for estimating the basal area growth of thinned stands such as these, for estimating mortality in the presence of effects of thinning level and site index, and for estimating site index in such young stands.

New information and techniques were derived from each of these studies for deriving components of the system.

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[2]Bennett, F. A. and E.P. Jones, Jr. 1965. A study of the effect of stand density upon growth and yield in slash pine plantations. USDA Forest Service Naval Stores and Production Lab., Cordele, GA. Establishment - Progress Report, Study 9.343, 38 p.

FIRST WEIBULL CHARACTERIZATION OF DIAMETER DISTRIBUTION

Analyses were first carried out to determine whether, according to the ordinary tests, the Weibull pdf. would yield adequate characterizations of the diameter distributions of these thinned and unthinned stands. First, Abernethy (1981) found that the three-parameter Weibull performed about as well for these thinned stands as for some unthinned ones (Bailey, Abernethy and Jones, 1981), and on that basis we proceeded to a second stage.

MODEL FOR BASAL AREA GROWTH

In developing a model for basal area growth, Bailey and Ware (1983) derived a new measure of kind and level of thinning and quantified its relationship to other stand attributes such as number of trees, basal area, and volume removed in thinning. This measure or thinning index is based on the ratio of the quadratic mean diameter of thinned trees to the quadratic mean diameter of all trees before thinning. The thinning index is then logically incorporated into a thinning multiplier from which is derived a compatible basal area growth projection model to generalize the previous concepts for thinning effects in systems for predicting growth and yield.

Empirical tests with data from thinned and unthinned natural stands of loblolly pine, from thinned and unthinned slash pine plantations, and from thinned western larch stands show the model to provide estimates with improved properties. The thinning index and thinning multiplier are, therefore, proposed for other situations involving effects of thinning.

MORTALITY ESTIMATING FUNCTION

Since prior models were inadequate to represent complex effects evident in these data, a mortality function sensitive to site index and thinning level was developed (Bailey et al., 1984). Changes in numbers of surviving trees in these repeatedly thinned old-field slash pine plantations were found to be significantly related to age, density, site index, and level and type of thinning. A model based on a difference equation formulation was derived and fitted with data from 824 growth periods from 289 plots. This is a logical extension of prior models to now express the effects of type and level of thinning, site index, and differential age effects. It is also compatible with the other models required for consistent growth and yield prediction for thinned stands. For these stands the mortality rate increased with site index, and it was accelerated by thinning from below in young stands. The mortality function accounts for these effects.

ESTIMATOR FOR SITE INDEX

On the basis of Abernethy's (1981) summary it appeared that there were shortcomings to the site index curves previously used. An equation form that would produce anamorphic curves at young ages and polymorphic curves at older ages seemed to be required. Therefore, new site curves were developed (Borders, Bailey and Ware, 1984).

The site index curves were improved by splining segments of two non-linear height-age models. An algebraic differences formulation for the growth

model eliminated the need to approximate derivatives. The splined site curves fit better than any single model across the entire range of data and have the desirable properties: (1) height is zero when age is zero, (2) height at base age equals site index, (3) each curve has a separate upper asymptote, and (4) the curves are invariant with respect to choice of base age.

PARAMETER RECOVERY OF DIAMETER DISTRIBUTIONS

WEIBULL DISTRIBUTION AS A BASIS

For fitting the Weibull distribution, we used FITTER (Bailey, 1974) with individual tree data rather than with diameter class summaries. All distributions were fitted twice with FITTER, once with "bias correction" and once "without bias correction".

Both procedures seem to fit about the same number of distributions well. Even though the estimates of individual Weibull parameters may be more biased when using the bias correction, the estimate of the quadratic mean diameter, a very important stand parameter, seems to be less biased. Since our goal is to predict distributions and sizes of trees rather than merely obtaining unbiased estimates of the parameters of a probability distribution function used in an intermediate step, we elected the "bias correction" procedure.

Diameter distributions in absence of thinning were predicted from the stand characteristics for two cases: Case 1) trees per acre (TPA), Site-index, (SI), AGE, and basal area (BA) observed; Case 2) only TPA, SI, and AGE observed. Prediction equations for this system are based on the 454 measurement periods during which no thinning was done.

Diameter distributions of the stand after thinning were then predicted from the distributions before thinning and a measure of the amount of thinning specified in any one of five ways:

1. to specified basal area (BA) and number of trees per acre (TPA), thus quadratic mean diameter, QD, is specified also
2. to a specified number of trees per acre (TPA),
3. to a specified basal area (BA).
4. to a specified stand table after thinning,
5. to remove a specified percentage of trees from each of 3 percentiles of the stand as it is before thinning.

RESULTS OF INITIAL FITTINGS OF MODELS

Prediction of the before-thinning stand table worked well. There were no cases for which the estimate did not converge for the "C" (shape) parameter of the Weibull.

For predicting the stand structure after thinning, given BA removed, TPA removed or both, we predicted changes in the 20th and 95th percentiles and in DQ based on type and intensity of thinning. We then solved iteratively for Weibull parameters C, B, and A. If this estimate of A (location parameter) was smaller than for the "before-thin" stand, we set A to the

same value as the before-thin A and then solved iteratively for B (scale parameter) and C again. In this we were attempting to avoid having increasing numbers of trees in any diameter classes after thinning. However, because we predicted changes in percentiles and DQ by equations that were separately fitted to the same data set, there were sometimes arithmetic artifacts caused by interactions when we solved for A, B and C. That is, in some cases the stand table after thinning might have a greater number of trees in some dbh classes than the stand table before thinning. Although a possible solution may have been to use some type of constrained estimation, rather than attempt developing new theory or procedures we elected to take a cosmetic smoothing solution. A subroutine (with user warnings) was written to determine when this decrease occurs and then to assign trees to adjacent diameter classes so there are no more trees in any dbh class after thinning than before thinning.

The problem is not common and if changes were necessary it was usually only a few trees in a couple of dbh classes. This problem did not occur for either of the other options that might be used to specify thinning. Thus, as always, the more information supplied by the user, the more reliable the predictions and projections.

In developing the projection system, we projected values for A, the 95th percentile, and DQ, then B and C were determined by interation. In some test cases of the projections, numbers of trees in the smaller dbh classes increased with time. Since the A parameter is conditioned to increase, it is not the cause. However when B and C are solved for, it sometimes happened that the C parameter decreases, thus causing an increase in the coefficient of skewness.

We considered several possible remedies:

1. Project 20th and 95th percentiles as well as DQ. This approach aggravates the problem.
2. Project A, C and DQ. Although this approach produces a quadratic in B, that could be solved and we developed projection equations for C (thinned & unthinned separately).
3. Project A, B, C
4. Consider alternatives to the Weibull-based diameter distribution projection system.

Projection of diameter distributions is never very straightforward, of course. There is so much variation (even in "uniform" plantations) that projection equations usually don't explain much of the variation encountered. It is, therefore, very difficult to assure projections that are always logical through time. These difficulties are related to the parameter recovery approach to characterizing diameter distribution through use of the Weibull and similar probability density functions.

CHARACTERIZATION AS PERCENTILE-BASED DISTRIBUTION

As a consequence of the difficulties of obtaining results that were fully satisfactory by the standards we imposed, as discussed above, we sought further alternatives. We considered systems like those proposed by Clutter and Allison (1974), as well as Clutter and Jones (1980). That system

involves a type of stand table projection in which diameter class limits are considered variable and are projected through time. The result is a stand table at the projection age with various sized diameter classes. These variable-sized diameter classes are not entirely satisfactory.

We developed a percentile-based system that has the desired flexibility and that fits well to our empirical data (Borders, Souter, Bailey and Ware, 1987; Borders and Souter, 1986). In this approach, stems-per-acre are proportioned into size classes based on percentiles and a simple uniformity assumption about frequencies in adjacent percentiles. The technique has also been described by Souter (1986) and will be discussed by Souter in these proceedings (Souter, Bailey and Ware, 1987).

PAST TENDENCIES AND FUTURE TRENDS

Parallel with trends elsewhere in growth and yield prediction, we had:

1. A good data base of several-times remeasured permanent plots with imposed thinning treatments.
2. State-of-the-arts computing power.
3. State-of-the-arts concepts for fitting and parameter estimation based on work in statistics and forest biometrics.
4. The rich background of empirical work on model building, model fitting and the logic of model formulation of our predecessors--especially Schumacher, Clutter and Bennett.

On that foundation we attempted to improve the structure of the models (systems) from two standpoints; (a) how well they correspond with our understanding of the biology of stand dynamics, and (b) how well-behaved they were logically and mathematically in characterizing internal relationships, compatibilities and consistencies. Naturally we also sought good statistical fits to the data within these bounds.

Now there are many new developments--some being reported in these proceedings--to improve the logical and mathematical structure and biological integrity of models. These approaches are very much advanced from the much more empirical earlier ones. "The formula of best fit" was often sought by a posteriori screening of a large array of regressions involving polynomial forms from a grab bag of independent variables. The kitchen sink isn't as often included nowadays.

Once we had, by the standards described above, derived conceptual formulations for our component models, we then sought procedures that would yield parameter estimates with desirable properties for each component model while retaining the desired internal structures, relationships and constraints. Next we sought to build these component models for basal-area growth, height/age relationships and mortality estimation into the compatible system and to estimate parameters for that system so that growth and yield estimates with desirable properties would ultimately be obtained.

Our work with the diameter distribution approach builds on many related developments and parallels work elsewhere. These developments have involved various probability density functions for dealing with unvariate

and bivariate distributions with bi-modality, etc. (Cao and Burkhart, 1984; Hafley and Buford, 1985; Schreuder and Hafley, 1977; Schreuder, Hafley and Bennett, 1979). Many novel approaches have been taken to cope with the vagaries of data and the difficulties of fitting.

Advancements in the conceptual formulation of models and in adapting them to conform to the data have brought the field to a natural plateau where higher priority can now be given to difficulties in fitting, in estimating parameters for the functions in the system and indeed in ascertaining the properties of parameter estimates. Increasing attention is now being given to estimating the parameters of these simultaneous sets of related equations--sometimes non-linear, almost always algebraically constrained--fitted to data that contain complex serial correlations and both logical and statistical dependencies and complicated variance-covariance structures for the residuals.

Except for the work, almost 20 years ago, of Furnival and Wilson (1971) most of this effort is quite recent. Among those attempting to improve our ability to estimate these parameters and ascertain their properties are Gregoire (1985), and Borders and Bailey (1986), and Gertner. Sadly enough, we seem to have reached an asymptote in improving the precision and unbiasedness of our estimates.

Even when the system has been constructed to satisfy the imperatives implied above, and the most sophisticated estimation techniques have been applied for the parameters of the functions, we still find our growth and yield systems to have several shortcomings. This is especially true when diameter distribution-based models built on relatively inflexible prior probability distributions are used to estimate for extreme values and infrequent combinations of the input variables under thinning. Since the extrema are often of most interest to a user he will always try your model beyond its limits! At that juncture, one or another of Murphy's Laws usually holds!

We, have tried our systems at extrema and found that while the performance may be adequate by usual standards of acceptability, there is always much more to be desired. As an alternative to dependency on prior distributions, we sought ways to place greater dependency on the observed distribution, ways to apply different apportioning schemes for dividing the stand into size classes, ways to make more potential use of and to link with stand inventory data in application and potentially in model development and calibration.

This parallels historical developments in growth and yield research. Emphasis was first placed on a purely empirical approach. Permanent plot data were often missing, computing power was rudimentary, and statistical concepts and methods were commensurately primitive by current standards. Subsequently, work swung, pendulum-like, toward a more abstract and theoretical basis with strong dependency on prior distributions. Now it is possible to shift emphasis once again toward the empirical; to use the experience we have now in model formulation and make greater use of specific stand and tree information both in model development and application.

Toward those ends, Daniels (1981) made early progress with an integrated approach that allowed a telescoping of compatible individual tree, diameter distribution and whole stand models. Others have been working on individual tree models and an aggregation approach to estimation for the stand. Key works on the distance-dependent models have included Mitchell (1975), Daniels and Burkhart (1975) and Tennent (1980). Foremost among distance-independent models of individual tree growth are the works of Ek and associates, first around FOREST (Ek and Monserud, 1974), and then around the North Central Forest Experiment Station's (eg., Leary, Holdaway and Hahn, 1979) STEMS/TWIGS systems. Somewhere intermediate between these approaches and ours is the work of Clutter and Allison (1974) Clutter and Jones (1980) and the continuing work of Stage and associates on the tailored PROGNOSIS system (Stage 1973).

There are other general developments that will be useful in steering and providing a kind of biologically defensible logic as well as improved estimation. Included are those on the "-3/2 rule of self thinning" and Oscar Garcia's (1984, 1987) stochastic differential equations models.

Lastly, there finally seems to be a trend toward attempting to link development and application of growth and yield prediction systems with growing stock inventories. For many years (eg., Ware and Hughes, 1974; Stage 1981; Ware, 1984) it has been evident that we need to link growth and yield predictions, calibration samples, monitoring samples, inventory samples, etc. It has not been evident how to do this. There now is progress from various new angles, for example, the work of Burk, Hansen and Ek (1981), Burk and Ek (1982), Green and Strawderman (1985), Gertner (1984), Walters and Burkhart (1987), and Droessler and Burk (1987). The work reported in these proceedings by Lappi and Bailey (1987) on height/age relationships also enables such linking with inventory data. This approach combines the features of traditional site-index models and models of the growth-intercept type. It allows all data taken at all ages to be used with a previously fitted model.

Several important side effects of these developments may be anticipated. They will serve much-needed validation, calibration, monitoring, and feedback functions to improve performance of local predictions and adaptations to new timber management technology, genotypes, etc. Also they should help us to deal with an important source of potential sampling bias not now explicitly considered in model development work.

All the techniques mentioned earlier to improve the estimates (e.g., reduce bias) of parameters are aimed at reducing potential effects of the internal structure of the sample used as a basis for deriving the system. They do not deal with the question of bias introduced by the way that sample was selected. This latter is no doubt a much larger source of bias, for we have not done much to improve our definition of target population and our rules for selecting the sample from that target population so as to control bias and precision when our predictors are applied. In fact, because of natural variation, it is almost impossible adequately to define our target population.

Many of the recent approaches are less dependent on prior assumptions about and even definition of the target population. These approaches will enable

us more fully to use inventory data and local stand data to monitor, calibrate and improve projection. In this way we may to some extent finesse the problem of defining a target population. We adapt the prior sample basis to the specific population of interest by a posterior sample taken from that specific population and combined with prior information.

One side effect of the level of mathematical and statistical sophistication of the approaches that are now on the cutting edge will be the stringent future requirement for very advanced training of modelers (and possibly users). As Oscar Garcia has pointed out for systems of stochastic differential equations, one needs to know what he's doing.

FORCASTING AND OTHER WIZARDRY

Substantial challenges remain in the art and science of developing systems for predicting growth and yield. Even with the most creative and advanced approaches there are many philosophical and statistical-theoretical difficulties in sampling and inference (Ware 1984). Modern information needs are for detailed predictions of future development of stands under rapidly changing production technology. In contrast, the early concerns were for stands subject only to natural processes; then the past yield of stands of matched condition would provide the basis for inference and predictions of the future development of similar stands.

To project stand development into the future under changed conditions, the processes become extrapolative and predictive, and statistical confidence limits cannot be established under the usual assumptions. Extrapolation, prediction, projection, and forecasting are all forms of prophecy on which our assurance is some subjective faith in their merit.

A model form that parallels our current understanding or abstractions of the biological processes of stand growth is generally expected to provide better predictions--at least we have higher faith in its merit--on general scientific if not statistical grounds. Particularly we expect it to give more "trustworthy" results when we evaluate the potential effects of managerial intervention in the stand processes through new production technology.

There is no neat scientific probability measure of the confidence we should have in predictions about the future. Nevertheless, we shall have more complex, more process-oriented, more locally calibrated and more empirically-based models. We shall certainly, therefore, have increased confidence in them. The developments are very promising.

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STAG: A FOREST STAND GENERATOR
for producing complete CACTOS stand descriptions

Greg S. Biging and Lee C. Wensel [1]

ABSTRACT.
The forest Stand Generator, STAG, estimates missing tree heights, height-to-crown base, or both to produce complete stand descriptions for use in the California Conifer Timber Output Simulator, CACTOS. Complete descriptions are also produced from stand tables or from the summary statistics of basal area and number of trees per acre by species. By producing a complete stand description, STAG ensures that most forms of inventory data can be analyzed by CACTOS to estimate future growth and yield under a wide array of silvicultural and management instruments.

INTRODUCTION

The forests of northern California are characterized by stands of mixed species as well as mixed ages and sizes. Inventories of these stands usually contain diameter at breast height (DBH) for each tree with only occasional measurements of heights and crowns. In other instances, only stand summary statistics or stand table data are recorded, and hence, no individual tree information is available. However, the California Conifer Timber Output Simulation System, CACTOS, (Wensel and others (1986), Meerschaert (1987), Wensel and Biging (1987)), requires that species, diameter at breast height (DBH), tree height (H), height to the crown base (HCB) or live crown ratio, and number of trees per acre be supplied for each tree making up the stand description. To to obtain the most accurate representation to project with CACTOS, these variables should be measured for all trees. Since inventory data sets are frequently incomplete, the forest Stand Generator, STAG, was developed to meet this need (Biging and Meerschaert, 1987)[2].

It is evident that the forest manager needs a means by which these data can be supplemented to form a complete stand description, as described above, so that individual tree growth and yield projection can be performed on the stands of interest for all different levels of data availability. This paper will discuss the operation of STAG, and present the estimation procedures used to (1) fill in missing measurements of tree height, height to the crown base or both; (2) generate stands from summary statistics and, (3) to convert stand table data, numbers of trees by DBH classes and species, to individual tree records so that stand descriptions can be analyzed by CACTOS.

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[2]The theoretical basis for this work and early versions of the program are given by Van Deusen (1984) and Van Deusen and Biging (1985). Thanks to Dr. Paul Van Deusen, U.S. Forest Service, for his review of this manuscript.

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PROGRAM OPERATION

STAG is a computer program that has three main data analysis routines, a configuration routine, and report writing capabilities (see Figure 1). The configuration routine allows the user to change default values of parameters that affect program output. Reports can be written from the three main routines for filling in missing data, converting stand table data (termed distributional apportionment), and generating stand descriptions. These latter routines are discussed below under estimation procedures.

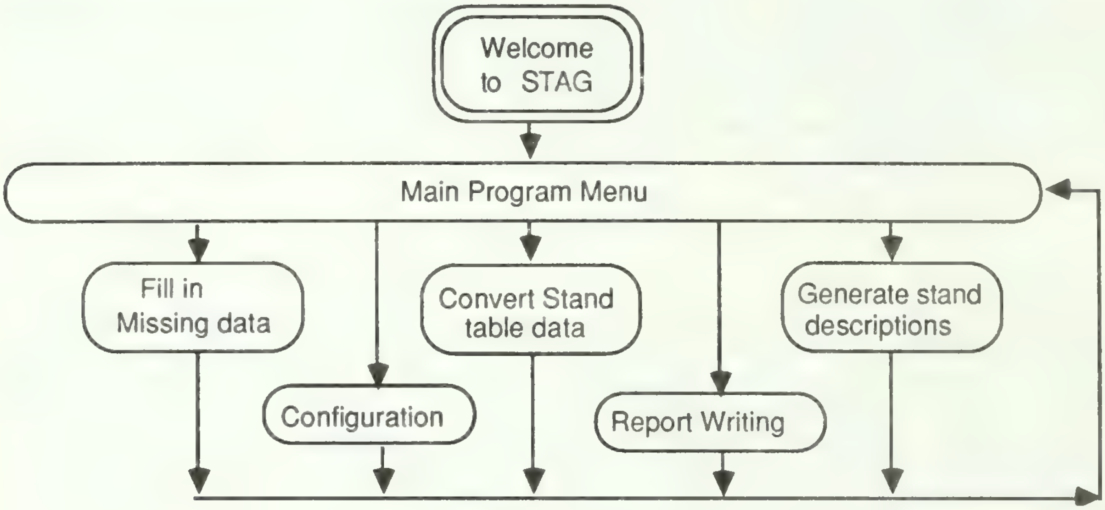

Figure 1. Structure of STAG, the forest STAnd Generator.

STAG is menu driven to enhance its user friendliness. The program is operated either by responding to questions from the program, or by typing two-letter commands in response to the main program menu prompt "stag:". A comprehensive list of the commands available from the main menu is printed when **pc** (print commands) is typed as displayed in Figure 2.

```
stag: pc

     MAIN COMMANDS

 cf  enter configuration routine
 ex  exit to operating system
*da  distributional apportionment
*md  fill in missing data
 pc  print commands
 sg  hypothetical plot generation

     OPTIONS:  [ > or  >>output]   [<input]

* =  can be run in batch by specifying dab or mdb

stag:
```

Figure 2. Main program menu of STAG

ESTIMATION PROCEDURES

STAG has three main data analysis routines and distinct statistical procedures used in each. Each of the three routines (filling in missing data, generating stand descriptions, and converting stand table data) are described below.

MISSING DATA

For cases where tree species, DBH, and trees per acre are available for all trees, but some or all heights, height to the crown base, or both are missing, STAG can be used to fill in these missing values. Tree heights are estimated by (Van Deusen (1984) and Biging and Meerschaert (1987)):

$$H = b_0 + b_1\sqrt{DBH} + b_2\sqrt{BA_6} + b_3E^2$$

where BA_6 is the stand basal area (ft^2) in trees greater than 5.5 inches in DBH,
DBH is the tree diameter (.1 in), and
E is the stand elevation in feet.

The coefficients b_0, b_1, b_2, and b_3 were estimated for 8 conifer species and 3 hardwood species using data from trees on permanent plots maintained by the industry members of the Northern California Forest Yield Cooperative. Sample sizes for each species ranged from a low of 340 observations for black oak to over four thousand observations on Ponderosa pine and white fir. All standard errors were in the range of 10 - 12 feet. Other model forms which included site index were evaluated, but did not outperform this model. For coefficient values and fit statistics in this and subsequent models refer to Biging and Meerschaert (1987).

To estimate height to the crown base (HCB), a model form based on the logistic equation was chosen so that HCB would be constrained to be between zero and total height. The form of the model selected was

$$HCB = H\left(1 - e^{-(c_0 + c_1 \ln BA_6 + c_2 (DBH/H))^2}\right)$$

where HCB is the height (ft) to the base of the crown,
H is total height (ft),
DBH is diameter at breast height (.1 in),
BA_6 is as defined above, and
c_0, c_1, and c_2 are coefficients estimated for each species.

Sample sizes were the same as in estimating the total height model, but standard errors were slightly less ranging between 9 - 11 feet.

Given these two equations, it is possible to "fill in" missing values of heights and height-to-crown base. In the above equations, elevation is the only additional variable that has to be supplied for each stand since BA_6 can be obtained by summing the individual tree basal areas obtained from tree DBH. The user has the option of adding stochastic errors to the deterministic predictions.

If the user wants to "localize" the height diameter relationship, STAG provides for a Bayesian update of the first two parameters of the height model. Alternatively, an ad hoc weighting scheme patterned after the linear composite estimators (Burk et al, 1982) can be chosen.

GENERATING STANDS FROM SUMMARY STATISTICS

If tree DBH is not available for all trees, but the total number of trees and basal area are known by species, then a diameter distribution can be generated and the tree heights and height to the crown base supplied as above. This is very useful for generating hypothetical stand descriptions where no actual tree measurements are available, or where only summary statistics are recorded.

The general theory behind STAG's models undertakes to characterize the joint distribution of species, DBH's, height, and height-to-crown base as being a product of probability density functions (Van Deusen, 1984) as:

$$p(D,H,HCB) = \sum_{s=1}^{S} p(\text{Species})\ p(\text{DBH} \mid \text{Species})\ p(\text{H} \mid \text{Species, DBH})\ p(\text{HCB} \mid \text{Species, DBH, H})$$

The joint probability distribution of DBH, total height and height-to-crown base (p(D,H,HCB)) is given as a product of conditional distributions. The fraction of each species in the stand (p(Species)) is specified by giving the number of trees per acre by species. The conditional distribution of diameter given species (p(DBH|species) is generated from a two-parameter Weibull distribution. With the two parameter Weibull distribution, the first moment corresponds to the average DBH of the species, and the second moment corresponds to the quadratic mean diameter which can be derived form basal area and number of trees for each species. Thus, if basal area of the species (SBA_6) and number of trees of the species greater than six inches in diameter (SN_6) are chosen as summary statistics, it is possible to derive the second moment of the two-parameter Weibull. We found that the first moment could be accurately predicted as a function of species basal area and numbers of trees in the species. Thus, the user can generate a diameter distribution for each species knowing only the number of trees and basal area in each species. Individual tree DBH's are then randomly generated using an inverse transformation method for the two-parameter Weibull.

Once the diameters are specified the height and height-to-crown base prediction equations (p(H|species,DBH) and p(HCB|species,DBH)) "fill in" the missing height and crown bases. Elevation also needs to be supplied since it is an independent variable in the height prediction model.

The factorization approach was taken over, say, a bivariate or trivariate approach, because of relatively small samples sizes occurring an any one plot and because with a factorization approach any number of species can be modelled.

To test this procedure we used approximately 200 one-fifth acre plots that were inventoried for tree DBH, height and height-to-crown base. For each plot an expected diameter distribution was generated by estimating the first and second moment of the 2-parameter Weibull distribution using SBA_6 and SN_6 as discussed above. The height and height-to-crown base prediction equations were used to "fill in" the missing height and crown information. It was shown that, on the average, the generated diameter distributions closely approximated the true distributions on these plots and that the predictive models provide relatively unbiased height and HCB estimates. For a more detailed treatment of this analysis see Van Deusen (1984).

CONVERTING STAND TABLE DATA TO AN INDIVIDUAL TREE LIST

One method for summarizing stand density information is to develop a stand table containing numbers of trees by DBH class and species. Usually the DBH classes are 1-2 inches or greater. Because trees are being tallied by diameter class, individual tree detail is not recorded. In this case the number of trees by DBH class provides a discrete approximation to the continuous diameter distribution and the approach used to obtain estimates of individual tree characteristics closely parallels that used for continuous data. For stand table data the distribution of grouped diameters given species (p(DBH | Species)) is assumed to follow a Weibull distribution. The probability of a tree height falling into some discrete height class given its species and DBH class (p(H | Species, DBH)), and the probability of a tree crown falling into some discrete class given its species, DBH and height class (p(HCB | Species, DBH, H)) are both postulated to be normally distributed. These assumptions were tested via a Kolmogorov-Smirnov test and found to be plausible.

DIAMETER DISTRIBUTIONS

Diameters of trees were assumed to be distributed across diameters classes in a fashion that follows a Weibull distribution. If the diameter classes are sufficiently small then it is reasonable to assume that the trees within a diameter class are uniformly distributed. In testing these assumptions on 50 quarter acre plots, we found that the simplifying assumption of uniformity within diameter classes produced results quite similar to assuming an overall Weibull distribution, provided the classes were two inches or less.

HEIGHT DISTRIBUTIONS

Using the diameter class mean value, an average value for height and height to the crown base is predicted from the equations shown under the section on missing data. The predicted values serve as a basis for locating the height distribution within a diameter class (see Figure 3). The variance of the distribution is approximated by the variance of the height predictive equation. Given these assumptions, the area under the curve for each height class provides an estimate of the proportion of trees in each category. Using this technique, the number of trees per diameter class can be apportioned over the range of height classes. Hence the nomenclature used to describe the process is termed distributional apportionment.

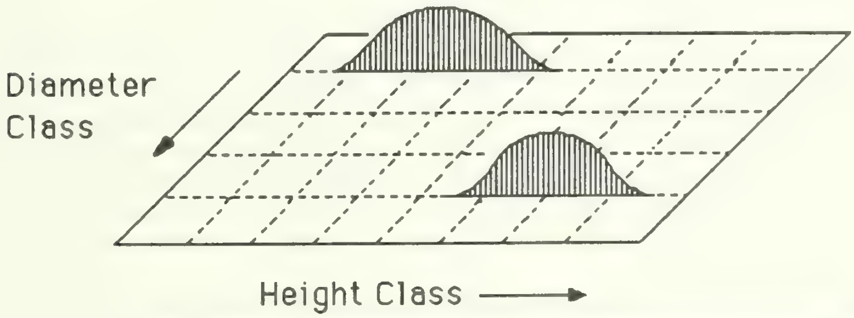

Figure 3. Distributional apportionment of stand table data.

HEIGHT-TO-CROWN BASE DISTRIBUTIONS

It is postulated that the distribution of crowns within a given height and DBH class is normally distributed. The allocation of numbers of trees to each of the crown classes is determined in the same fashion as for heights. First, the normal curve is located using the

mean crown height value assuming the midpoints of the height and diameter class. Next the variance of the normal curve is approximated by the variance about the height-to-crown base predictive model. In the third step, the area under the curve above each crown class is calculated and the number in each height-diameter cell over the crown class is determined according to these proportions.

The apportioning process calculates the numbers of trees to place in each cell of the height-diameter-crown categories. Individual tree measurements are then given an equal probability of occurring at any location within the cell. Specific locations are randomly assigned by drawing random numbers which correspond to x,y,z coordinates in three dimensions. This procedure produces a list of pseudo-individual tree measurements from the original stand table data.

To test this procedure we used 50 quarter-acre plots that were inventoried for tree DBH, height and height-to-crown base. From this data we created "known" stand tables. We then used the stand tables to apportion the trees over height and crown classes. The numbers of trees apportioned into these classes corresponded well with the actual numbers observed on the plots. For a more detailed treatment of this analysis see Van Deusen (1984).

DISCUSSION

The Stand Generator, STAG, was created to ensure that complete individual tree lists would be available for analysis in the conifer growth and yield system CACTOS. STAG utilizes predictive equations for total height and height-to-crown base developed from a permanent plot system of over 40,000 trees in Northern California. To attack the problem of stand generation, i.e. converting summary statistics to psuedo-individual tree records, STAG factors the joint distribution for species, DBH, H, and HCB into a product of probability density functions and models each of these components. Using this approach it was possible to model the relatively small numbers of trees occurring in any one plot. The methodology developed for converting stand table data closely follows that described for stand generation.

These procedures have been tested with permanent plot data and have been shown to produce reliable and relatively accurate results. However, there is no substitute for real data. The procedures in STAG are not meant to replace complete inventory data. Rather, they were created to increase the pool of inventory data that can be used for projection in CACTOS. The stand generation and stand table conversion techniques should be used only to gain insight in how stands of a given description are likely to grow, not as a routine method for making growth projections with CACTOS. Given this caveat, STAG has proven to be a powerful tool in the CACTOS System. Because of the large research quality data base used to derive the height and height-to-crown base models, users have found these predictive equations to be reliable and often more accurate than "filling in" values based upon small locally derived equations. If the user has high quality local data, STAG's predictions can be modified to give higher weight to the local sample than is indicated by its relative sample size. STAG's other routines for converting stand table data and summary statistics to individual tree values have given users a very flexible system for accessing CACTOS when there is a paucity of individual tree data, but judgment should be exercised in its use.

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MODELLING INDIVIDUAL TREE GROWTH FROM TEMPORARY PLOT RECORDS

Terry D. Droessler and Thomas E. Burk[1]

ABSTRACT. Periodic independent samples within a stand or covertype do not provide a real growth series for individual trees. Differences between fixed percentiles of diameter distributions of varying ages do provide tree growth information if macro-site differences are controlled. However, sampled percentiles may still decrease in size unless the age difference is large enough. This decrease is caused by sampling error and micro-site differences.

Smoothing the sample-based diameter distribution can provide a potentially better paradigm of the population. Goodness-of-fit comparisons of the raw cumulative distribution function with those resulting from fitting a nonparametric and Weibull density to the raw distribution are presented based on three simulated forest stands. Change models can be fit to the smoothed percentiles. The resulting models can be considered individual tree growth models. Simulation work indicates that appropriate methodology applied to temporary plot data can provide parameter estimates comparable to fitting the same model to permanent plot records. However, parameter estimates can vary considerably depending on attributes of the temporary plot data. It is hypothesized that a component of these differences is real biological variation that only surfaces with permanent plot based models when they are evaluated using independent data.

INTRODUCTION

Continuous forest inventory (CFI) systems with repeatedly measured permanent plots are being de-emphasized in favor of periodic stand description inventories based on independent, temporary plots. Ek et al. (1984) noted the situation in the Lake States (Michigan, Minnesota and Wisconsin). Most CFI systems involve relatively low sampling intensities; temporary samples are commonly used to supplement the permanent samples for inventory purposes. These facts have important implications for forest growth prediction where most models have been developed from permanent plot data. In particular, refinement of individual tree growth models is thought to require individual tree data of the type commonly obtained from CFI systems. The decision to maintain CFI systems for developing or refining individual tree growth models should be based on the availability, expense and quality of alternative growth data. Temporary plot data is generally more available and less expensive than permanent plot data. However, methodology for individual tree growth model development from temporary plot data is lacking. One possible methodology is presented in this report.

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DESCRIBING DIAMETER DISTRIBUTIONS

Tree diameter at breast height (DBH) is a continuous random variable for a population of trees. Therefore, a DBH population distribution function is smooth and continuous while the sample distribution may be rough in appearance. One rationale for fitting a distribution function to DBH distributions is to smooth the distribution in hopes of making it more like the underlying population and facilitate making probability statements about DBH intervals.

The Weibull distribution function has commonly been used to represent DBH distributions because of its flexibilty. Bailey and Dell (1973) discuss the desirable features of the Weibull for quantifying DBH distributions. In contrast, nonparametric density estimation makes no assumptions of the underlying distribution shape. The data are allowed to determine the density estimate without being constrained to a distribution family. Two nonparametric methods considered in this study are the kernal (Tarter and Kronmal, 1976; Silverman, 1986) and the frequency polygon--averaged shifted histogram (FP-ASH) (Scott, 1985; 1987).

MONTE CARLO COMPARISON OF ALTERNATIVE DIAMETER DISTRIBUTION DESCRIPTIONS

The Weibull, kernal and FP-ASH distributions represent three alternative techniques for smoothing a sample DBH distribution. A Monte Carlo simulation study was designed to answer the following: (1) whether smoothing a sample DBH distribution would improve its representation of the known (constructed) population from which it was drawn; (2) whether smoothing is beneficial over a range of populations and sample sizes and; (3) if so, which method of smoothing is best for the population and sample size combinations considered.

Three hypothetical populations of tree DBHs were constructed from red pine (Pinus resinosa Ait.) plantation CFI data: bimodal, left-truncated and thinned. DBH data were pooled over several plots and then values deleted until the desired distribution shape was obtained. The bimodal population was the first constructed and a bimodal shape was achieved with 1011 trees. The other population sizes were thus fixed at 1011 trees. The bimodal population mimics a stand where 7 and 9 inch DBH trees dominate, resulting in distribution peaks at these DBHs. The left-truncated population represents a stand with only trees greater than or equal to 5 inches DBH. The thinned population was constructed from plots which had been selectively harvested or thinned. Thinned distributions are generally multimodal.

One thousand samples of size 30 and 1000 samples of size 10 DBHs were drawn from each population. The 10 tree samples were subsamples of the 30 tree samples. The two sample sizes were chosen to reflect two levels of sampling intensity, approximately 3% and 1% for the 30 and 10 tree samples, respectively.

The vertical discrepency between the population and sample, Weibull, kernal and FP-ASH cumulative distribution functions (cdfs) is a useful basis for goodness-of-fit comparisons. The median absolute vertical difference (mavd) at sample percentiles (cdf step points) was used as an

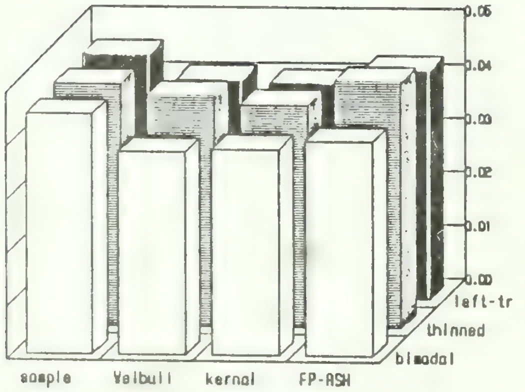
indicator statistic of goodness-of-fit between the population and sample based cdfs. The percentiles at which the vertical DBH differences were compared were i/30, i = 1,...,30 and j/10, j=1,...,10 for the 30 and 10 tree samples, respectively. For a given sample of 30 (or 10) trees:

(1) Let d_j be the DBH at the j^{th} percentile in the sample.
(2) Let ph_j be the value of the population cdf at d_j.
(3) Then $vd_j = ph_j - j/100$ and $avd_j = | ph_j - j/100 |$.

This defines a percentile based comparison of a sample cdf with a population cdf. Percentiles for the Weibull were obtained by solution of its cdf. Percentiles for the kernal and FP-ASH cdfs were obtained from the density functions by combined use of quadrature and zero finding algorithms.

The median of 1000 mavds between the respective population and sample, Weibull, kernal and FP-ASH cdfs for sample sizes 30 and 10 are presented in Figure 1. The Weibull, kernal and FP-ASH cdfs have smaller mavds than the sample cdfs for the three populations. Therefore, smoothing a sample DBH distribution can improve its representation of the underlying population. The one exception is for the thinned FP-ASH cdf with n = 30. No single best method for smoothing the 30 tree samples for the three populations is apparent. However, the FP-ASH had the lowest mavds for the 10 tree samples for all three populations and thus was chosen for further work. In general, smoothing improves upon the actual sample with smoothing consistently more beneficial for the 10 tree samples than for the 30 tree samples for the three populations considered.

a.



b.

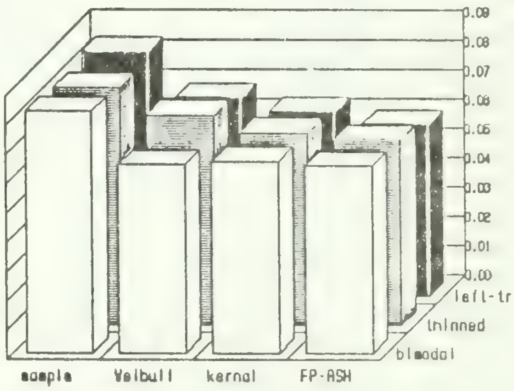


Figure 1. Median absolute vertical differences between the population and sample, Weibull, kernal and FP-ASH cdfs for sample sizes of 30 (a.) and 10 (b.) tree DBHs.

A METHOD FOR MODELLING DIAMETER GROWTH FROM TEMPORARY PLOT RECORDS

The proposed methodology for modelling individual tree DBH change requires temporary plot measurements at several ages within a specific covertype or stand. Each temporary plot of tree DBHs can be smoothed using an FP-ASH. Tenth percentiles (0.1, 0.2,..., 0.9) from each FP-ASH can then be calculated. A time series of percentiles (for example, a sequence of deciles from FP-ASHs arranged in time) is considered a surrogate for DBH growth. Parameters for a DBH change equation can then be estimated from the sequence of percentiles.

Following Borders et al. (1984), an algebraic difference formulation of Schumacher's (1939) volume-age equation was considered to model DBH change over time.

$$D_2 = D_1 e^{b\left(\frac{1}{A_1} - \frac{1}{A_2}\right)} \qquad [1]$$

where D and A represent DBH and age at times 1 and 2 and b is a parameter. Equation [1] was linearized by taking natural logarithms of both sides. All possible regressions through the origin were calculated using the log ratio of DBHs as the dependent variable. The following equation was chosen as a generalized difference equation based on the root mean square error (rmse) statistic from a number of candidate equations.

$$D_2 = D_1 (B_1)^{b_1} (A_1)^{b_2} e^{b_3\left(\frac{1}{A_1} - \frac{1}{A_2}\right)} \qquad [2]$$

where D, A and B represent DBH, age and basal area at time 1 or 2, and b_1, b_2 and b_3 are parameters.

Baselines are necessary against which the temporary plot methodology results can be compared. Two baselines were used: 1) equation [2] parameters were estimated from a true growth series and then used to project remeasured plots and 2) GROW (Brand, 1981), a Lake States regional growth model, was used to project remeasured plots. The temporary plot based equation [2] was also used to project remeasured plots. The projection results using the three methods were then compared.

Projections were conducted as follows. The first actual DBH was used as DBH_1. DBH_1 was then projected to measurement 2 at which time actual and projected DBH were compared. The projected DBH_2 was then projected to measurement 3 and so on until the final measurement. Trees that died were eliminated from the projection along the way. This eliminated the influence of mortality on comparisons.

DATABASES

Two permanent plot databases were selected: 1) Star Lake Plantation (Wilson, 1963) and 2) Birch Lake Plantation (Martin, 1978). Temporary

plot databases were constructed from the permanent plot databases. Constructing all possible plot time series (except where one plot is repeatedly measured over the growth periods) simulates the variability that can occur using temporary plot data. In fact, many time series may be unreasonable if the plot age and density values are quite different. Using nine equally spaced percentiles, a percentile dataset consists of 9*(number of measurements - 1) observation pairs of percentile change.

A temporary plot dataset of percentile change pairs for 5 plots with 5 measurements on each plot can be represented as follows:

$D_{g,i,n+1}$, $D_{h,i,n}$ where D is the DBH for:
$g,h = 1,2,3,4,5$ $g \neq h$ (plot numbers)
$i = 1,2,\ldots,9$ (deciles)
$n = 1,2,3,4$ (measurements)

The Star Lake permanent plot database consists of 4 plots with 6 measurements on each plot. A total of 1080 temporary plot DBH sequences were constructed from the permanent plot data (Droessler, 1987). Two nonconsecutive measurements from a plot were allowed, therefore this temporary plot dataset contains a partial real growth series. The Birch Lake permanent plot database consists of 7 plots with 5 measurements on each plot, or a total of 35 plot-measurement DBH distributions. By permuting seven plots, five at a time, a total of 2520 temporary plot datasets were constructed. Each dataset consisted of the deciles from different plots arranged in a time series as described above. In contrast to the Star Lake temporary plot datasets, the Birch Lake temporary plot datasets do not contain any real growth series information.

The majority of temporary plot datasets contained some decreases in percentiles over time because of micro-site gradients between plots. These datasets were unsuitable for estimating equation [2] parameters. A parameter "screen" was developed to allow parameters similar in sign and magnitude to the permanent plot based parameters to be used in projecting the permanent plots. One screen resulted in 282 out of 1080 and 400 out of 2520 parameter sets for Star Lake and Birch Lake respectively, as appropriate to estimate parameters for projection.

Figures 2 and 3 compare the permanent plot, GROW and temporary plot based projections of the Star Lake and Birch Lake permanent plots in terms of a mean absolute (mad) and mean difference (dbar) between the actual and projected DBHs by measurement number. The mad and dbar statistics for the permanent plot (ppd), the GROW and the temporary plot (tpd) based projections represent the average over all trees on a plot and over all plots. For the Birch Lake database (Figure 3), the permanent plot based projections had the lowest and the temporary plot based projections had the highest mean absolute and mean DBH differences over the measurement span. In contrast, the mean absolute and mean DBH differences in Figure 2 show the temporary plot projections as slightly better than the GROW projections over all but the last measurement number.

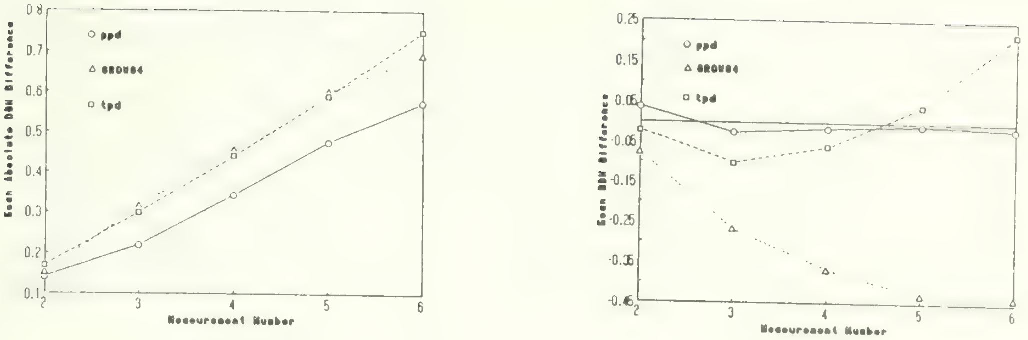


Figure 2. The mean absolute and mean difference between the actual and projected DBHs for Star Lake using the ppd, GROW and tpd based parameter estimates.

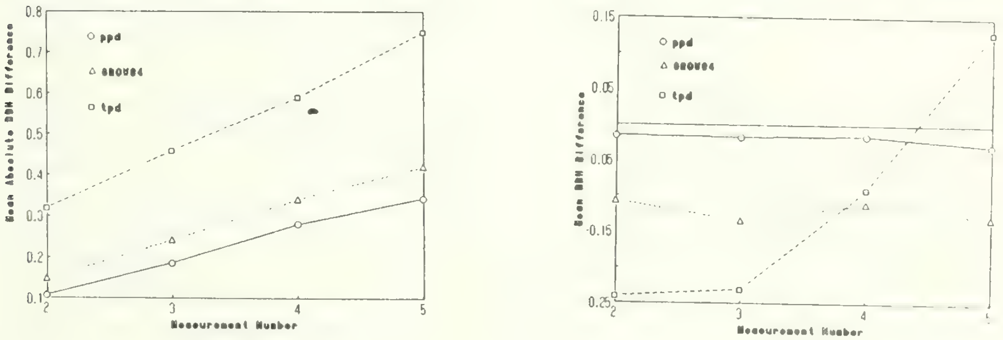


Figure 3. The mean absolute and mean difference between the actual and projected DBHs for Birch Lake using the ppd, GROW and tpd based parameter estimates.

Two conclusions can be drawn from the results. 1) Nonparametric density estimation techniques provide a more flexible alternative to the Weibull distribution for smoothing the distribution of tree DBH in stands of trees. In particular, the nonparametric FP-ASH density was chosen as the best method for smoothing plot DBH distributions based on Monte Carlo simulation results for three populations and two sample sizes. 2) The temporary plot methodology, when used with a combination of permanent and temporary plot data (as with the Star Lake temporary plot dataset), can rival a regional growth model for projection for local datasets.

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DEVELOPMENT OF AN INDIVIDUAL TREE GROWTH MODEL FOR PENNSYLVANIA

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ABSTRACT. Preliminary results from the development and testing of an individual tree growth model for species commonly found in Pennsylvania are presented. The model predicts growth in tree basal area as a function of species, diameter, basal area, stand basal area, basal area in the stand in trees larger than the subject tree, and site class. Results of tests of the ability of the model to predict short term survivor growth have been good, but further work is needed in model refinement.

INTRODUCTION

The Commonwealth of Pennsylvania has a large timber resource characterized by a diversity of species, age structures, site quality, and products. Although recent studies have shown that the state's timber growth far exceeds the drain (Lord, 1985; Powell and Considine, 1982), concern for the timber supply in the future suggests the need for a statistically accurate and biologically sound model of tree and stand growth.

The most valuable hardwood species in Pennsylvania are black cherry and red and white oak. These trees commonly occur in mixed stands. The implication is that any growth model constructed must be capable of simulating the development of all species, not just the species of value. So, although models for white oak (Hilt, 1985; Dale, 1975) and red oak (Hibbs and Bentley, 1984) in other parts of the northeastern United States have been developed, there is still a need for a model similar to TWIGS or STEMS which can handle any type of stand.

This paper describes results from the initial phases of developing such a model using data from Pennsylvania forest stands. The model is similar to STEMS in that one model form is used for all species, but coefficients in the model change from species to species. Tree basal area growth is the dependent variable, as in the central states version of STEMS (Shifley, 1987). Unlike STEMS, site quality is represented by site class (1, 2, or 3), rather than site index. The other major difference is that data restrictions precluded using any type of crown measurement (e.g., crown ratio, crown class, etc.), as is done in STEMS.

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The data for this study are from permanent plots established and maintained by the Pennsylvania Bureau of Forestry. All 431 plots are 1/5th acre (0.1 ha.) in size, and are located on State Forest land. The number of measurement occasions range from two to four, with remeasurement cycles ranging from 5 to 9 years. The oldest plots in the data set were established in the early 1960's. Over 30 species are represented; their relative abundance is illustrated in Figure 1. The preponderance of chestnut oak (Quercus prinus) is indicative of State Forest land, but not of Pennsylvania forest land in general. Nevertheless, enough data are available for each species to allow the development of a model that should work anywhere in the state.

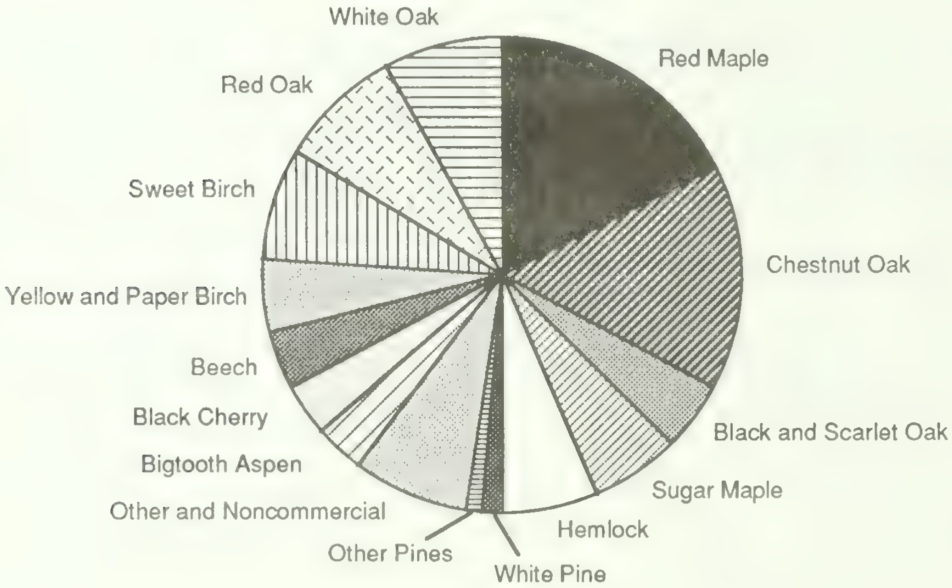

Figure 1. Relative abundance of species represented in the Pennsylvania Bureau of Forestry data set.

Species selected for this preliminary study were red oak (Q. rubra), white oak (Q. alba), sugar maple (Acer saccharum), and black cherry (Prunus serotina). These species represent a range of tolerance classes, and are the most valuable from a commercial viewpoint. Descriptive statistics are provided in Table 1. Individual tree records for each species were allocated either to a calibration data set, for model fitting, or to a validation data set, used for testing. Average diameter at breast height (DBH) is only for those trees greater than or equal to 5.0 inches DBH.

A major feature of the model to be described is the use of site class as a predictor variable. The Bureau of Forestry used the following definitions for this variable:

> Site 1 - Characterized by moist, well-drained, fairly deep soils which usually occur in protected coves, along streams, or in bottomlands that remain moist throughout the year.
>
> Site 2 - Characterized by soils intermediate in moisture, depth, drainage and fertility and which dry out for only short periods during the year.
>
> Site 3 - Characterized by the shallow, rather dry, stony or compact soils which usually occur on ridges or broad, flat plateaus.

Original plans for development of this model called for the use of crown class as a predictor variable (Fairweather, 1986). Unfortunately, crown class was not collected on the plots until the most recent remeasurement occasions, so it was not available for consideration.

TABLE 1. Descriptive statistics for data sets used in development and testing.

Species	Number of Obs.	Avg. No. of Grow. Seas.	Avg. DBH (in.)	Avg. Tree BA Growth (sq.ft./yr)	Stand Basal Area (all sp.) (sq.ft./a)
			Calibration Data		
S. Maple	758	6.8	7.8	.008	105.9
B. Cherry	394	6.9	10.5	.015	105.3
Red Oak	932	6.4	10.9	.019	94.4
White Oak	712	6.7	9.6	.011	92.0
			Validation Data		
S. Maple	749	7.0	8.2	.009	107.6
B. Cherry	414	7.0	10.4	.014	105.4
Red Oak	901	6.9	10.0	.018	83.0
White Oak	915	6.3	8.1	.008	76.1

MODEL DEVELOPMENT

The STEMS models have featured the prediction of either diameter growth (e.g. the Lake States version) or basal area growth (the Central States version). The advantages of working with basal area growth were described by Shifley (1982). Basically, the linear correlation between basal area growth and tree basal area is stronger than that between diameter growth and diameter. This was supported by observations on white oak (r=.658 vs. r=.333) and on eastern hemlock (*Tsuga canadensis*) (r=.647 vs. r=.230).

Basal area growth (BAG) was modeled as the product of potential growth and a modifier, as is done in STEMS. The form of the potential growth function was

$$POT = ((a \cdot TBA^{b}) - c \cdot TBA) \cdot (d + eX1 + fX2) \qquad (1)$$

where POT = potential annual basal area growth (square feet),
TBA = tree basal area (square feet),
X1 = 1 if Site 1, otherwise = 0,
X2 = 1 if Site 2, otherwise = 0,
and a,b,...,f are coefficients to be estimated for each species.

The modifier function serves to represent the competition in the stand surrounding the subject tree, and reduces the potential growth estimate to a more reasonable estimate of basal area growth. The form of the modifier function was

$$MOD = g \cdot [1.0 - \exp(-((h/BAL)+(i \cdot DBH^{2})) \sqrt{BATERM})] \qquad (2)$$

where MOD = a fraction of potential basal area growth,
BAL = basal area per acre (sq. ft.) in trees larger in DBH than the subject tree,
DBH = diameter at breast height (in.) of the subject tree,
BATERM = (1.0-(BAA/250)), where BAA is total basal area per acre (sq. ft.),
and g,h,i are coefficients to be estimated for each species.

Basal area growth for any particular tree is then predicted as

$$BAG = POT \cdot MOD. \qquad (3)$$

Equation (3) was fit for the four species in two stages. First a data set suitable for the construction of the potential growth function was constructed. This involved finding the average BAG in each site class/TBA cell, and the associated standard deviation. The standard deviation was multiplied by 1.65, and added to the mean for the cell, in the manner of Hahn and Leary (1979). These observations became the dependent variable in equation 1, which was fit using nonlinear regression (module PAR in BMDP).

In the second stage, observed BAG for each tree in the calibration data set was used as the dependent variable, POT was calculated and used as an independent variable, and the coefficients in equation (2) were found through nonlinear regression. The values of the coefficients are shown in Table 2.

TABLE 2. Equation coefficients for potential and modifier functions.

	B. Cherry	S. Maple	Red Oak	White Oak
Potential function				
a	.138760	.808006	.253500	.178929
b	.737760	.724995	.609515	.675331
c	-.009687	-.137356	-.047995	-.059031
d	.189921	.054756	.172510	.186419
e	.094247	.020000	.104309	.102212
f	.054364	.003333	.057939	.056756
Modifier function				
g	.726743	.479412	.552020	.646893
h	35.528600	130.512366	97.333000	50.333525
i	.016823	.002129	.002529	.007157

It is interesting to note that the values of the coefficients in the modifier function are of the same magnitude as those in the central states STEMS model, even though the forms of the potential growth models are different. For example, in the STEMS model the values for g,h, and i for white oak are .49141, 75.41, and .006791.

MODEL EVALUATION

Table 3 shows coefficients of determination (R-squared) for a simple linear regression of observed BAG on predicted BAG, based on equation (3), using the validation data. Also shown is the root mean squared residual for each species, obtained when fitting the function to the calibration data. The last row of the table shows the mean difference between the predicted and observed basal area growth for trees in the validation data set.

TABLE 3. Statistical evaluation of basal area growth model.

	B. Cherry	S. Maple	Red Oak	White Oak
R-squared:	.61	.54	.57	.48
Root MSR (sq.ft):	.0085	.0059	.0106	.0064
Shifley (1982):	-	.0097	.0118	.0086
Mean residual (pred. - obs.)	.000412	-.000009	-.001360	-.000009
Shifley (1982):	-	-.004300	-.001076	.000000

The results in Table 3 are comparable to those obtained by Shifley (1982) in his preliminary attempts at a basal area growth model for the central states. His model utilized crown ratio in the potential growth function, but, based on these few results, it seems to add little to the predictive power of the model.

A more meaningful evaluation of the growth model involves testing it in the same context in which it may be used, e.g. in an inventory update application. In this preliminary study, several plots from the data set with at least 85% of their basal area in the four species were selected for evaluation. For each plot, the basal area per acre at two remeasurement occasions was compared to the model's prediction of basal area at those times. The projections assumed "perfect knowledge" of mortality and ingrowth, since these models have not been developed yet.

The results of some of these comparisons are shown in Figure 2. Observed and predicted basal areas were nearly identical for the red oak and for the sugar maple/black cherry plots. The model performed very well for a plot predominantly in black cherry. The development of sugar maple in a nearly pure stand was steadily overpredicted. An understocked plot with a mixture of red and white oak was steadily underpredicted. Two plots with high proportions of white oak (not shown) were predicted to grow faster than they actually did.

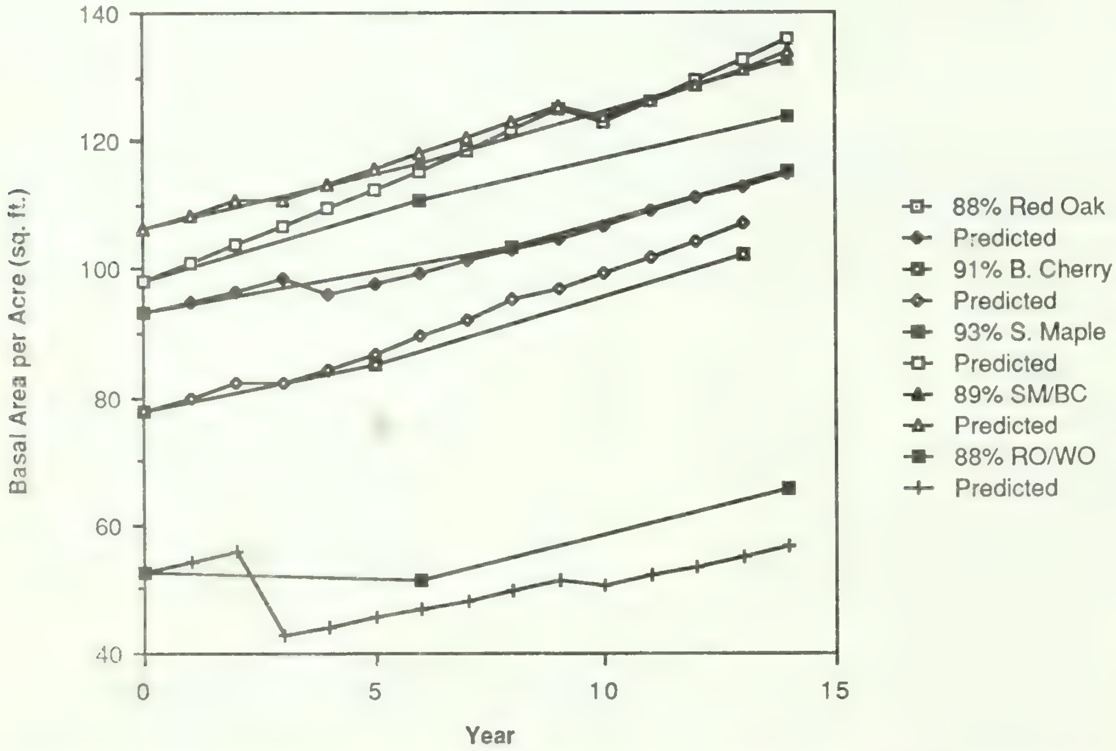

Figure 2. Comparisons of observed and predicted basal area for several plots in the data set.

Although more testing is necessary, the fact that the model tends to grow surviving trees too fast suggests that the potential growth function needs to be further analyzed. Perhaps the impact of site class is not as simple as the model would suggest; some of the analyses during model calibration suggested there may be a tree basal area/site class interaction that should be included in the model.

Another factor to consider in future work is the impact of the gypsy moth and oak leaf roller on the development of hardwood tree species. These influences were not controlled in this preliminary study, and may be affecting the test results.

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COMPARISON OF SOME INDIVIDUAL-TREE HEIGHT-INCREMENT MODELS FOR WESTERN HEMLOCK AND SITKA SPRUCE IN SOUTHEAST ALASKA

by Wilbur A. Farr and Ralph R. Johnson[1]

ABSTRACT. Multiple-linear and nonlinear height-increment models were tested on data bases containing 1259 western hemlock (Tsuga heterophylla (Raf.) Sarg.) and 1171 Sitka spruce (Picea sitchensis (Bong.) Carr.) young-growth trees in southeast Alaska. Periodic 10-year height increment was best predicted using linear models in which the dependent variable was not transformed. Nonlinear, modified potential-growth models have appeal, but more needs to be learned about stand dynamics of hemlock and spruce before they can be used with high precision.

INTRODUCTION

An individual-tree, distance-independent growth model is being developed for the western hemlock (Tsuga heterophylla (Raf.) Sarg.)-Sitka spruce (Picea sitchensis (Bong.) Carr.) forest type of southeast Alaska.[2]

The model, referred to as SEAPROG (SouthEast Alaska PROGnosis), is one of 12 variants of PROGNOSIS (Wykoff and others 1982) currently under development or available in the western United States.[3] The principal components for the SEAPROG model are diameter growth, height growth, and mortality. Site index is used instead of habitat type in SEAPROG because even-aged management is applied in this forest type. Habitat type was used in PROGNOSIS and some of its variants calibrated mostly for multi-species uneven-aged stands.

Diameter and height-growth functions in PROGNOSIS were developed using linear regression in which the logarithm of 10-year diameter or height growth was used as the dependent variable (Wykoff and others 1982, Stage 1975). Other developers of individual-tree growth models have used nonlinear, modified potential-growth functions to estimate periodic

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[3]Unpublished user's guide, 1987, "Growth and yield submittal system users guide," by Kathy Sleavin, U.S. Department of Agriculture, Forest Service, Washington Office Timber Management Unit, 3825 Mulberry Street, Fort Collins, CO 80524.

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diameter growth, height growth, or both (Richie and Hann 1986, Wensel and Koehler 1985, Martin and Ek 1984, Daniels and Burkhart 1975, and Arney 1972). Periodic growth in these models is estimated from the product of a tree's potential growth and a measure of competition, which restricts the tree's ability to reach its potential.

During the development of SEAPROG, we compared untransformed-linear, log-linear, and nonlinear, modified potential-growth functions for estimating periodic 10-year height growth. A similar comparison for diameter growth was not possible because functions for potential diameter growth were not available for western hemlock or Sitka spruce. The objective was to develop the best possible models for height growth of western hemlock and Sitka spruce.

STUDY AREA

Data for the study came from even-aged stands in southeast Alaska. The forests of this region are part of the temperate western hemlock-Sitka spruce rain forest that extends along the Pacific coast from near Coos Bay, Oregon, north and west to the Alaska Peninsula, spanning about 22 degrees of latitude and a distance of about 2,900 kilometers. The forests of southeast Alaska are productive for their latitude, and changes in mean site index with latitude are predictable, decreasing northward at the rate of about 1.04 meters of site per degree of latitude (Farr and Harris 1979). Climate is relatively uniform and mild, especially near sea level (Farr and Hard 1987).

The western hemlock-Sitka spruce forest type occupies about 5.3 million hectares in coastal Alaska, about 2.8 million hectares of which is classified as commercial forest land. Virgin stands of hemlock and spruce predominate, with small percentages of western redcedar (*Thuja plicata* Donn ex D. Don) and Alaska cedar (*Chamaecyparis nootkatensis*)(D. Don) Spach). Only about 158,000 hectares of commercial forest land have been harvested since 1900, and 4,000-7,000 hectares are now harvested annually. All harvesting is by clearcutting.

Natural regeneration after clearcutting is excellent on all but a few sites, and new stands contain several thousand stems of hemlock and spruce per hectare. Once established, growth rates are relatively high. When stands reach 25 to 30 years of age, crown closure approaches 100 percent and remains so for 100 years or more unless thinned.

In 1974, a long-term cooperative study was started to measure the effects of stand density on growth and development of natural even-aged stands of hemlock and spruce in southeast Alaska.[4] Since then, 278 0.4-hactare plots, have been installed on Federal, State, and private lands, and more are being added each year. The data base for these plots was used to develop the height-growth functions for SEAPROG.

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[4]Unpublished study plan, 1976, "The effects of stand density upon growth and yield of hemlock-spruce stands in coastal Alaska. Revised study plan," by Wilbur A. Farr, U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, P.O. Box 020909, Juneau, AK 99802.

DATA

Data for this study came from 163 stand-density plots installed in southeast Alaska between 1974 and 1976. All plots were in natural even-aged stands covering as wide a range of age, site, and species composition as possible. Most plots, however, were located on relatively high-site lands because mature stands have seldom been harvested on lands of poor site quality.

Shortly after being installed, about 75 percent of the plots were thinned; the remainder were unthinned. Plots in young stands were precommercially thinned to 2.4-, 3.6-, or 4.9-meter spacing; plots in older stands received a similar light, medium, or heavy thinning, in which spacing was a function of mean stand diameter at the time of thinning.

These permanent growth plots have been remeasured at 2-year intervals since installation to obtain detailed growth and mortality data. Mean stand age and site index (Farr 1984) were determined separately for hemlock and spruce on each plot. Diameters to the nearest 0.25-cm and crown class of all trees were recorded at each remeasurement. A subsample of trees (10 to 15 per species per plot) was measured for total height and height to live crown to the nearest 0.3-m with a clinometer.

A computer program was written to backdate the latest measurements in the data base 10-years so that periodic 10-year height growth could be estimated for each tree, along with estimates of all key variables at the beginning of the period. Backdating was necessary because a full 10 years of measurements were not available in the data base. Crown ratio was assumed constant over the period.

The data set for all trees contained 12,692 trees. Hemlock and spruce trees were selected for this study if they had repeated height measurements, were free of top damage or other severe damage, and were at least 6.4 cm in diameter at the beginning of the 10-year period. In total, 1259 western hemlock and 1171 Sitka spruce were selected. Means and ranges of key variables for the subsample of trees are presented in table 1.

Table 1. Means, minimums, and maximums for site index and six tree variables.

	Sitka spruce (N=1171)			Western hemlock (N=1259)		
Variable	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Site index (m)	28.7	10.5	36.1	24.9	10.5	34.0
10-year height growth (m)	4.4	0.4	10.6	4.1	0.4	10.7
Breast height age (yr)	32	5	81	40	3	95
Height (m)	19.5	2.3	40.1	18.5	4.3	37.2
DBH (cm)	25.4	6.4	76.1	22.9	6.4	63.1
10-year diameter growth (cm)	6.6	0.1	21.0	4.4	0.1	16.7
Crown ratio	0.39	0.05	0.85	0.40	0.05	0.75

Linear and nonlinear height-increment models were tested. Linear models were similar in form to the model developed by Stage (1975), and improved for use in PROGNOSIS (Wykoff and others 1982). Nonlinear models were similar to those used by Arney (1972), Martin and Ek (1984), and Richie and Hann (1986). Crown competition factor (CCF) and other measures of competition (Wensel and Koehler 1985, Daniels and Burkhart 1975) were not tested because, at the time of the study, they were not available for hemlock and spruce in southeast Alaska.

Linear Models

Stage (1975) developed a linear height-increment model in which the logarithm of 10-year height growth was used as the dependent variable. This model was later improved for use in PROGNOSIS (Wykoff and others 1982). It was of general form:

$$\ln(HTG) = f(HAB, SPP, HT, DBH, DG, HT^2);$$

where: HTG = periodic 10-year height growth of individual trees,
HAB = habitat type,
SPP = species,
HT = total height,
DBH = diameter at breast height, and
DG = periodic 10-year diameter growth.

We tested two similar models except that the dependent variable was not transformed. In the first, the continuous variable SITE was substituted for habitat type, and the variable crown ratio (CR) was added. The model was of form:

$$HTG = b_0 + b_1(SITE) + b_2HT + b_3DBH + b_4DG + b_5HT^2 + b_6CR \qquad (1)$$

The second model included log transformations of independent variables diameter, diameter growth, crown ratio, and height, and was of form:

$$HTG = b_0 + b_1(SITE) + b_2HT + b_3DBH + b_4DG + b_5HT^2 + b_6CR$$
$$+ b_7\ln(DBH) + b_8\ln(DG) + b_9\ln(CR) + b_{10}\ln(HT) \qquad (2)$$

In addition to fitting these two models through stepwise regression, we also investigated the need to transform the dependent variable as previously found necessary in PROGNOSIS (Wykoff and others 1982).

Nonlinear Models

The nonlinear models tested were of general form:

$$HTG = PHG * CM;$$

where: PHG = potential height growth derived from height growth curves,
and CM = modifier resulting from competition.

Application of modified-potential height-growth models assumes that potential height growth follows the height-growth curves--from current

height to height 10 years in the future. Current effective age is not known here, but is estimated from stand site index and individual tree height.

Height-growth equations for hemlock and spruce in southeast Alaska (Farr 1984) are log-linear in form, and inverting them to solve for current effective age, given site index and tree height, is not possible. New nonlinear equations were therefore developed that can be inverted. Data points for the new equations were obtained from solutions to the log-linear height curves for hemlock and spruce (Farr 1984), and then fit to an equation of form:

$$H = ((S/(1-\exp(-b_1 50)^{**}(b_2 S^{**}b_3))) * (1-\exp(-b_1 A))^{**}(b_2 S^{**}b_3));$$

where: H = height - 1.4 meters,
S = Site index - 1.4 meters, and
A = tree age at breast height.

A fit of this equation assures that height = site at index age 50 years.

An estimate of current effective age at breast height is obtained by inverting the above equation and solving for age given site index and mean height of the 100 largest diameter spruce and hemlock per hectare. Addition of 10 years to this age and solution of the equation yields an estimate of height 10 years later. More complete details of the procedure are in Wensel and Koehler (1985).

Competition modifiers have been tested in previous analyses. Three were fit to the hemlock and spruce data in nonlinear models of form:

$$HTG = (PHG)*b_1(1-\exp(b_2 CR^{b_3})), \tag{3}$$

$$HTG = (PHG)*b_1(\exp(b_2 BA)), \text{ and} \tag{4}$$

$$HTG = (PHG)*(b_1(1-\exp(b_2\ CR))*(\exp(b_3((RELHT)^{b_4} - 1))));\tag{5}$$

where: PHG = potential height growth,
CR = crown ratio,
BA = basal area per hectare in trees 1.3 cm and larger,
RELHT = total tree height divided by mean height of the 100 largest diameter trees of the same species per hectare.

Model (3) was used by Arney (1972), model (4) by Martin and Ek (1984), and model (5) by Richie and Hann (1986). Other models that included measures of competitive stress (Krumland 1982, Daniels and Burkhart 1975) and crown area at 66 percent of tree height (Wensel and Koehler 1985) were not tested because measurements of these variables were not available.

RESULTS AND DISCUSSION

Parameter estimates and R^2 values for linear models 1 and 2 are presented in table 2, and for nonlinear models 3 to 5 in table 3.

Table 2. Coefficients, R^2's, and standard errors of estimates for three multiple linear growth models that predict periodic 10-year height growth of western hemlock and Sitka spruce in southeast Alaska.

Variables and Statistics	Species, models, and dependent variables			
	Sitka spruce		Western hemlock	
	1 HTG	2 HTG	1 HTG	2 HTG
Variables				
Constant	-1.39902	-1.74968	-0.29703	-2.49668
HT^2	-3.85805E-3		-3.93442E-3	
SITE	0.14151	0.13814	0.11660	0.11320
ln(CR)		2.46948		
ln(DBH)		2.01658		2.09728
ln(HT)				
DG	0.09251	0.09247	0.17499	
.18680				
HT		-0.21073		-0.19231
DBH	0.05698		0.07470	
CR	3.00478		0.91670	
Statistics				
R^2	0.5097	0.5277	0.4069	0.4169
Se[a]	1.3942	1.3683	1.3970	1.3852

a/ Standard error of estimate.

Table 3. Coefficients, R^2's, and standard errors of estimate for three nonlinear models that predict periodic 10-year height growth of western hemlock and Sitka spruce in southeast Alaska.

Coefficients and Statistics	Species and models[a]					
	Sitka spruce			Western hemlock		
	(3)	(4)	(5)	(3)	(4)	(5)
Coefficients						
B_1	1.00513	0.92209	1.02088	0.95020	0.92473	0.94674
B_2	-4.73141	-2.34569E-4	-4.73378	-15.50897	5.90951E-6	-8.33653
B_3	0.92951		-0.18295	1.25468		-0.31495
B_4			3.06086			1.58590
Statistics						
R^2 [b]	0.4340	0.3658	0.4766	0.2219	0.2039	0.2716
Se[c]	1.5000	1.5871	1.4429	1.6022	1.6199	1.5508

a/ (3) $HTG = (PHG)*b_1(1-\exp(b_2 CR^{b_3}))$

(4) $HTG = (PHG)*b_1(\exp(b_2 BA))$

(5) $HTG = (PHG)*(b_1(1-\exp(b_2\ CR))*(\exp(b_3((RELHT)^{b_4} - 1))))$

b/ Decimal equivalent of percent of variation accounted for by regression.

c/ Standard error of estimate.

Periodic 10-year height growth for both hemlock and spruce appeared to be best characterized by multiple linear model (2) where stepwise regression was used to select the best fit among untransformed and log-transformed independent variables. Next best was equation (1), followed by nonlinear potential growth models (5), (3), and (4). Stepwise selection of variables in equations (1) and (2) probably provided better fits to these data sets than was possible for the nonlinear models because no selection process was provided for in the nonlinear models.

The models always fit the spruce data better than the hemlock data. Best R^2 values were about 0.53 for spruce and 0.43 for hemlock. Minimum standard errors of estimate (Se) were about 1.4 meters for both hemlock and spruce.

Plots of residuals from equations (1) and (2) convinced us that transformation of the dependent variable was not needed to meet the assumptions of regression. As a further test, we fit model (1) to the hemlock and spruce data with a log-transformation of the dependent variable as used in PROGNOSIS (Wykoff and other 1982). Histograms and normal probability plots of standard residuals from these runs showed much poorer fits to the data, confirming that transformation of the dependent variable was not needed for hemlock or spruce. Similar results were recently found by Dolph (in preparation) for six mixed-conifer species in the Sierra Nevada of California. Dolph's data, like ours, were from young-growth stands (his for trees less than 80 years old at breast height). Results of these two studies suggest that log-transformation of periodic 10-year height increment may not be necessary for young-growth trees, but may be appropriately used to decrease the variance of residuals associated with older trees.

Periodic diameter increment was the most important independent variable correlated with periodic height increment, followed by site index and height. Live crown ratio was important in the linear models for spruce, but was of minor importance or nonsignificant in the linear models for hemlock. The relative importance of live crown ratio was also apparent in nonlinear models (3) and (5) where R^2 values were much higher for spruce than for hemlock.

For western hemlock, linear model (2) was clearly superior to nonlinear, modified-potential growth models (3), (4), or (5), and marginally better than model (1).

Linear models also appeared best for Sitka spruce; however, the two-variable, modified-potential growth model (5) performed very well. With additional testing and a better understanding of stand dynamics of hemlock and spruce, the modified-potential growth models can likely be developed to equal or better the performance of the five variable linear models.

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ADAPTION OF THE 'STEMS' GROWTH MODEL TO EUCALYPT FOREST

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ABSTRACT. STEMS is a distance-independent tree growth model developed for major tree species in the Lake States region of the U.S.A. The development of a similar model for use as a simulator of *even* and *uneven-aged* eucalypt growth in Tasmania, Australia is described. Australian mensuration has not been geared towards the modelling of uneven-aged forest growth and this first attempt to do so for Tasmanian forest reveals some major problems. Most serious is the fact that site index cannot be estimated for uneven-aged forest in the conventional way because trees in this type are not aged. Alternative estimators of site productivity based on height growth and ecological indicators are considered, and the efficacy and utility of the adapted model are discussed.

INTRODUCTION

Multi-aged eucalypt forest is extensive throughout the forested regions of Australia, and although typically low yielding compared with single-aged stands, it has significant commercial and recreational value. Yet, few serious efforts have been made to model its growth.

This paper reports an adaptation of the growth component of STEMS (Stand and Tree Evaluation and Modelling System) for multi-aged eucalypt forest in the State of Tasmania, and describes a technique used to estimate site index for multi-aged forest which is compatible with a conventional age-dependent index.

DATA

Tasmania's 1.6 million hectares (4.0 M acres) of State forest is sampled by over 2,000 Continuous Forest Inventory (CFI) plots established since 1960, and re-measured every 5 to 10 years. About half of these are in multi-aged forest. Plots typically measure 100 x 20 m. A centre-line divides the plot into two 10 m wide corridors; in one corridor all trees with diameters over 10 cm are measured, but in the other, only trees larger than 40 cm are measured. 'Measurement' of a tree includes diameter and a range of crown factors such as depth, width and density, and the relative amount of light received.

Most plots in multi-aged forest, and some in single-aged forest, are not aged, primarily because of the difficulty of taking

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increment cores (or conducting stem analyses) in hardwood species. On plots which are not aged, height and bark thickness are sampled over the range of diameters. On aged plots,in contrast, only the tallest trees are heighted for the purpose of estimating 'dominant height' and site index. There are approximately 1,200 un-aged CFI plots, and 890 of these, which have been measured more than once, provide a data set for model development and evaluation.

Growth models can be broadly categorized as distance dependent or independent, single tree or stand simulators. Often, the choice of model is limited by the existing inventory. In this case, CFI plots are shaped and measured in a way that precludes distance-dependent models because of boundary effects. However, the detailed measurement of trees, particularly of their crowns, invites investigation of a distance-independent single tree growth simulator. STEMS is one such simulation model which appeared to be adaptable to Tasmanian forest inventory.

OUTLINE OF 'STEMS' GROWTH COMPONENT

The growth component of STEMS was developed for pure or mixed species, single or multi-aged stands in northern-central U.S.A. The current model consists of a 'potential growth' function (Hahn and Leary, 1979; see Equation 1); a 'modifier' function (Holdaway, 1984; see Equation 2) which estimates the fraction of potential growth actually allowed; and a 'crown ratio' function (developed by M. Holdaway but cited by Belcher et al., 1982; see Equation 3), used for long term growth prediction.

$$\frac{\Delta D_{pot}}{\Delta t} = a_1 + a_2 . D^{a_3} + a_4 . (SI.CR.D)^{a_5} \tag{1}$$

$$MODIFIER = 1 - e^{-f(R).g(AD).\left[\frac{BA_{max} - BA}{BA}\right]} \tag{2}$$

$$CR = \frac{d_1}{1 + d_2 . BA} + d_3 . \left[1 - e^{-d_4 . D}\right] + CF \tag{3}$$

where: $\Delta D_{pot}/\Delta t$ = potential annual diameter increment,
D = initial DBH,
SI = site index,
CR = (ratio of crown depth to total hight) x 10,

$$f(R) = b_1 . \left[1 - e^{b_2 . R}\right]^{b_3} + b_4$$

$$g(AD) = c_1 . \left[AD + 1\right]^{c_2}$$

BA_{max} = maximum basal area for a species,
BA = initial stand basal area,
AD = average diameter,
R = D/AD,
CF = a constant correction factor for each tree,
$a_1..a_5$, $b_1..b_4$, $c_1..c_2$, $d_1..d_4$ are coefficients.

SITE INDEX ESTIMATION

Site index on aged CFI plots is the estimated height of selected dominant trees at age 50 years. The consequence of age not being measured is that site index cannot be estimated in a conventional way. An index of site quality is a potentially useful parameter for estimation of growth, particularly in managed stands, and one which is required in the STEMS model. Consequently, a large proportion of the work presented here was devoted to developing an estimate of site index for unaged stands which was compatible with the conventional index. A technique was developed which used a weighted combination of three separate estimates derived from i) interpretation of aerial photography, ii) height growth and iii) estimation of mature height using height-diameter curves.

A. AERIAL PHOTOGRAPHY

The estimation of mature forest height using aerial photography is standard practice for CFI plots. If mature trees are not present on the plot, then mature trees in the near vacinity are used. Estimated mature height is categorized in plot records as:
E1: >55 m, E2: 41-55 m, E3: 27-41 m, E4: 15-27 m, and E5: <15 m.

Photographically derived mature height class was included with a range of factors in a discriminant analysis (SPSSX) designed to discriminate between pre-defined site index classes on aged plots. Parameters from aged plots included the coded occurrence or absence of 18 tree species, 13 understory and 10 grass types, estimated rainfall, slope and geology. Mature height class was found to be the most powerful factor in discrimination, and the best classification resulted from the alignment of site index class boundaries with mature height class boundaries using a site index function developed for *Eucalyptus obliqua* (A. N. Goodwin, unpublished; see Equation (4)). Using only mature height class in the analysis resulted in the percentage of correctly classified cases dropping from 50% to 46%. The simplification of using only mature height class, rather than a complex combination of factors,

to estimate site index on un-aged plots justified the marginal loss in classification accuracy.

$$SI = H.\left[\frac{1 - e^{-0.0424\ (50)^{0.859}}}{1 - e^{-0.0424\ AGE^{0.859}}}\right] \tag{4}$$

where: SI is site index (height at age 50 years),
H is dominant height

Table 1 shows means and standard deviations within mature height classes for aged plots. Standard deviations are large compared with the range of observed site indices (9 - 55 m at age 50 yrs), making the technique on its own unsatisfactory for estimation of site index. However, in conjunction with other estimates, it was regarded as potentially useful. Table 1 also shows mean site index for E1 and E2 to be similar, implying that in order for height potentials to be realised, height growth in the E1 category must greater than in the E2 after age 50 yrs. In other words, trees in E1 and E2 catagories may be growing along growth curves of different shape. This violates conditions for the use of anamorphic growth curves in this work. Unfortunately data were not available to develop polymorphic curves for Tasmanian eucalypts.

TABLE 1: Means and standard deviations for site index within mature height classes for aged plots.

Mature Height Class	Mean SI	Standard Deviation	Intervals
E1 (>55)	36.8	5.9	164
E2 (41-55)	35.3	7.2	711
E3 (27-41 m)	29.7	7.4	406
E4 (15-27 m)	23.3	6.7	48
E5 (<15 m)	14.0†	7.0†	0

†Extrapolated values.

B. HEIGHT INCREMENT

For plots measured two or more times, an estimate of site index is possible using height and height increment, and any set of non-intersecting site index curves for which age can be algebraically isolated on the left hand side of the function. Assuming that two

height measurements for a particular tree lie on the same predefined growth curve, then a function can be derived relating measurement interval to H_1 and H_2. In this case, using Equation 5, we have:

$$A_2 - A_1 = \Delta t = f(H_2) - f(H_1) \qquad (5)$$

where: A_2 and A_1 are ages at measurements 1 and 2,

$$f(H) = \left\{ \frac{-\ln\left[1 - H.SI^{-1}.\left[1 - e^{-\gamma_1.50^{\gamma_2}}\right]\right]}{\gamma_1} \right\}^{-\gamma_2}$$

$\gamma_1 = 0.0424$ and $\gamma_2 = 0.859$

Equation (5) can be solved for site index using the iterative Gauss-Newton method. Thus an estimate of site index can be derived from each measured tree, site index for the plot being averaged over the several estimates from selected trees.

Site index is conventionally derived on aged CFI plots using the mean height of the tallest tree on each $1/30^{th}$ hectare subplot. A similar sampling scheme was employed to select tree-derived site indices for incorporation in an estimate of plot site index. The effect of the sub-plot size, the number of trees selected from each sub-plot and the time between measurements on the accuracy and precision of the plot site index estimate was examined using aged plots. The resulting estimate of conventional site index was not biased using either the mean or the median of up to ten selected trees per 0.2 hectare plot. Medians were used in preference to means because they had smaller residuals, and a subplot size of $1/40^{th}$ hectare chosen primarily because they were easily identifiable on CFI plots. Equation (6) relates the variance of the median of tree-derived site indices given the number of estimated indices (N) and the length between measurements (Δt).

$$VAR_{\Delta H} = (4.53 - 0.351.N + 8.41/\Delta t)^2 \qquad (6)$$

C. HEIGHT VS DIAMETER FUNCTIONS

The principle behind the use of height-diameter functions was to estimate an asymptote for height which could be interpreted as mature height. Having found an asyptote, height at age 50 yrs can be estimated using anamorphic site index curves (see Equation 4).

The accuracy with which mature height could be estimated depended on the degree of stand development. Most well stocked multi-aged stands and old single-aged stands showed sufficiently well-

developed height-diameter trends to allow mature height to be estimated with confidence. However, some poorly stocked and young plots showed no inflection in their height-diameter trends, and provided no sensible estimate of mature height.

Height-diameter pairs for the first and last measurement of each plot were fitted with a Chapman-Richards function (Pienaar, 1973; Equation (7)):

$$H = \beta_1 . \left[1 - e^{-\beta_2 . D} \right]^{\beta_3} \tag{7}$$

where: β_1, β_2 and β_3 were the coefficients to be estimated.

Equation (7) was fitted using Bard's program for non-linear parameter estimation (NLPE) (Bard, 1967). The standard error of estimated mature height was approximated using the standard techniques for linear regression (Snedecor and Cochran, 1980) at the point where the slope of the fitted curve was 0.05. In this way, uncertainty about mature height was related to the degree of stand development. Determining the variance of the corresponding site index estimate was more difficult, since the accuracy of the anamorphic site index equations, developed specifically for *E. obliqua* (albeit the most widespread eucalypt in Tasmania), could not be determined. However, because this technique was regarded as being more discerning in well developed stands than the weighted mean the other two estimates, its estimate of site index needed to be weighted in a way that reflected this belief. This was achieved (somewhat crudely) by putting variance of the site index estimate equal mature height variance plus 15. By so doing, the smallest variances using this technique were made to be about 75% of the variance of the weighted mean of estimates from the other techniques (i.e. about 25). The three estimates were amalgamated into a weighted mean using weights propotional to the inverse of estimate variance. Unfortunately, the accuracy and precision of the amalgamated estimate of site index cannot be tested without time consuming field trials.

An alternative index of site quality was considered. This was an estimate of maximum height at a diameter under bark of 60 cm using equation (7). The combined weighted estimate of mature height using the aerial photography (A) and height growth (B) methods described above provided a prior distribution for β_1 in the baysian estimation of parameters (NLPE). This index explained marginally less variability when used in the adapted STEMS model.

ADAPTED MODEL

POTENTIAL INCREMENT FUNCTION

No account was made for species differences in this work. Although it will be investigated in the future, site index was thought to explain a large amount of species variation.

An important difference in the measurement of Lake States and Tasmanian trees is that crown ratio is scored on a ten point scale in the Lake States and on only a four point scale in Tasmania. The degree of resolution for the Tasmanian crown ratio was considered inadequate for sensitive model development and was replaced with a Crown Volume Index (CVI), which is the product of crown ratio and a subjective five point measure of crown spread relative to diameter.

Theoretically, CVI ought to be a more useful crown index than crown ratio. Because diameter growth is largely a function of crown size and density the STEMS growth model in effect explains variability in growth due to crown spread and density given crown ratio and diameter. Since CVI is an explicit measure of crown size given diameter, use of CVI removes one source of variability in estimation of growth.

Potential increment was determined using diameter under bark. Use of DBHUB is especially important for multi-aged eucalypt growth modelling since fire is a common occurrence in these forests and bark thickness can be significantly affected from measurement to measurement. Diameters under bark were calculated for each species at each measurement using three parameter Chapman-Richard functions (substitute bark for height in Equation (7)) for which the shape coefficients (β_2 and β_3) had been pre-determined for each species. At each measurement therefore, only β_1 needed to be estimated.

Data were catagorized into classes of diameter (5 cm), site index (4 m) and crown volume index (3 units wide) and the 95th percentile calculated for each cell in the manner described by Hahn and Leary (1979). Potential diameter increment was modelled with weighted least squares using Equation (8). Parameter estimates and standard erors are shown in Table 2. Although Equation (8) explained only 29% of variation in observed potential increment, this was typical of R^2 values for individual species in the Lake States (see Hahn and Leary, 1979, page 25).

$$\Delta D_{pot}/\Delta t = a_1 + a_2.SI + a_3.CVI + a_4.CVI^2 + a_5.(SI.CVI.D)^{0.1} \qquad (8)$$

where: $\Delta D_{pot}/\Delta t$ is potential annual diameter increment,

CVI is crown volume index,

$a_1 \ldots a_5$ are regression coefficients.

TABLE 2. Parameter estimates and standard deviations for Equation (8).

	Parameters						
	a_1	a_2	a_3	a_4	a_5	R^2	S^2
Estimates	0.58	0.024	0.10	-0.0044	-.030	0.29	0.81
Standard Errors	0.14	0.0023	0.018	0.0011	0.078		

MODIFIER

The modifier function in STEMS accounts for sub-optimal growth due to competition and other effects. Since competition is expressed largely in terms of crown size, which is now built into the adapted potential increment function, the adapted modifier ought simply to account for decreased crown density due to competition. Indeed, examination of many combinations of variables found the measure of 'crown density reduction', a subjective four point mesure on CFI plots, to be the most important variable.

Growth modification might also be expected to be affected by site occupation or crowding. Holdaway (1984) recognized this, and expressed site occupation in terms of current and mamximum basal area (see Equation (2)). However, this appears to be a problem because site occupancy is not necessaily a function of basal area. Rather, it is related to the proportion of the site's growing capacity currently being used. A 'closed' canopy is generally regarded as an indication of full site occupancy. This may happen before 10 years of age, yet basal area continues to accumulate until senescense.

Site occupancy in this work was regarded as the proportion of maximum leaf surface area currently on the site. An index of eucalypt leaf surface area was calculated by a method suggested by Mr. E. J. Lockett of the Tasmanian Forestry Commission (unpublished). If a crown is regarded as consisting of a hemisphere subtended to a cylinder, then the surface area of the crown (SAC) is given by:

$$SAC = 2.\pi.R^2 + 2.\pi.R.L$$

where: R is the radius of the hemisphere and cylinder,
L is the length of the cylinder,
and, given crown ratio (CR) and crown width (CW), it can be shown that:

$$SAC \propto CR.CW.D.H$$

Note that the product of CR and CW is the crown volume index (CVI). Now, leaf surface area (LSA) is taken to be proportional to the product of crown surface area and a crown density reduction factor. Total tree height (H) was estimated using yet another Chapman-Richards function relating height to site index and diameter taken over all aged plots. Leaf surface area for a single tree is given by Equation (9):

$$LSA \ \alpha \ D.CVI.SI.DEN.\left[1- e^{-0.0154.D}\right]^{0.654} \tag{9}$$

and maximum leaf surface area per hectare ($SLSA_{max}$), calculated using Equation (9), was found to be well described by the the linear function:

$$SLAS_{max} = -36.5 + 5.13.SI$$

Given a measure of site occupancy, a modifier function was defined by Equation (10). An arbitary constant was added to the site occupancy factor to ensure that MOD > 0. Parameter estimates and standard errors are shown in Table 3.

$$MOD = 1 - e^{-\left[b_1 \ + b_2.DEN \ + b_3.DEN.CAN\right].\left[0.01 + \frac{SLSA_{max}-SLSA}{SLSA_{max}}\right]} \tag{10}$$

where: DEN is a density reduction rating between 0 and 1, where DEN = 1 means no reduction,
CAN is a 4 point measure of the amount of light recieved by the crown, where CAN = 1 means maximum light.

TABLE 3. Parameter estimates and standard errors for Equation (10).

	Parameters				
	b_1	b_2	b_3	R^2	S^2
Estimates	0.135	1.47	-0.26	0.35	0.092
Standard Errors	0.089	0.11	0.02		

CONCLUSION

The model was evaluated using plots set aside for evaluation (one quarter of available plots). Projection intervals ranged from 4 to 13 years with a mean interval of about 7 years. The residuals were standardized to 7 years. The mean of the residuals was 0.51 cm, indicating an appreciable positive bias relative to the mean diameter increment of 2.11 cm. The standard deviation of the residuals (1.66) also compared poorly with the standard deviation

for diameter increment (1.99), indicating that the model explains little of the original variability in increment.

The reason for the model's poor performance is not clear. It is possible that the subjective crown measures were too coarse and that site index was poorly estimated. Amalgamation of species may also have been a contributing factor. It is also felt that the potential growth function may have been influenced by erroneous measurements in diameter and bark thickness. Future work in multi-aged modelling will examin the utility of single function growth models.

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INDIVIDUAL-TREE DIAMETER GROWTH MODEL FOR NORTHERN NEW ENGLAND[1]

Donald E. Hilt and Richard M. Teck[2]

ABSTRACT. A distance-independent, individual-tree diameter growth model is developed for 14 species groups in northern New England. Potential periodic annual diameter growth is modeled for each species as a function of dbh and site index. Potential growth is then modified according to the basal area per acre larger than the subject tree.

INTRODUCTION

Reliable growth and yield models are essential to the sound management of forests in northern New England: Maine, New Hampshire, and Vermont. Mixed-species stands dominate the region, and a multitude of past cutting practices has resulted in many stands that have indeterminate age and size structures. An individual-tree modeling approach is perhaps best suited for describing growth under these complex conditions (Hilt et al. 1987). Individual-tree models can also provide a framework for tracking information on the three factors that determine tree value: species, size class, and quality.

A distance-independent, individual-tree growth and yield simulator being developed for the Northeast will include three major components: diameter growth, mortality, and ingrowth. In this paper we discuss the development of an individual-tree diameter growth model for northern New England. Forest Inventory and Analysis (FIA) data were used to develop the model. Potential periodic annual diameter growth is first modeled for each of 14 species groups as a function of dbh and site index. The potential growth is then modified for each tree according to the basal area per acre larger than the tree.

DATA

Forest survey (FIA) data from northern New England were used to develop the diameter growth model. Individual-tree information for more than 2,000 1/5-acre permanent plots was available for analysis. Two remeasurement periods were available for Maine, and one for both New

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Hampshire and Vermont. The number of years between remeasurements ranged from 11 to 13. After editing, every fourth plot was systematically removed from the calibration data set and reserved as a source of data for validating the models.

Information recorded for each tree greater than 5 inches dbh included species, initial dbh, and dbh 11 to 13 years after the initial measurement. Site index was also recorded on each 1/5-acre plot for the dominant species. We used site-index conversion equations to assign the appropriate site index to each tree depending on its species. We computed various tree- and stand-level variables such as number of trees per acre, basal area per acre, quadratic mean stand diameter, ratio of tree basal area to plot basal area, and basal area per acre larger than the subject tree (BAL). The calibration data were divided into 14 species groups for analysis (Table 1).

ANALYSIS AND RESULTS

Each of the 14 species groups was analyzed separately. The data were grouped into cells based on the range of values for the independent variables. Cell means were then computed and used as observations for the analysis. We used cell means to reduce the total number of observations so that various nonlinear model forms could be examined more efficiently. Individual-tree periodic annual basal-area growth was the dependent variable. The relationship between tree basal-area growth and tree size is graphically more distinct for study than the relationship between diameter growth and tree size (Hilt 1983). Numerous model forms and combinations of independent variables were examined (Hilt et al. 1987). We report here only on the final model selected for application.

POTENTIAL GROWTH

Individual trees for a given species were sorted in descending order according to their basal-area growth rates in each dbh x site-index class. The top 10 percent of the fastest growers in each class were then selected to develop the potential growth function. A modified Chapman-Richards (Richards 1959) model was used to predict the growth rates of these fastest growers. Site index was added to the model as a linear term, i.e., potential growth increases linearly with site index for a given dbh:

$$POTBAG = b_1*SI*(1.0-EXP(-b_2*DBH)) \qquad (1)$$

where POTBAG is the potential basal-area growth for an individual tree, and b_1 and b_2 are parameters that were estimated with nonlinear regression techniques. An investigation of the error structure revealed that cell variances were not correlated with dbh or site index. Therefore, each observation was weighted only by the number of trees in each cell for the regression analysis.

The fitted values for b_1 and b_2 are shown in Table 2, and the resulting equation is plotted in Figure 1 for the predominant softwood and hardwood species in northern New England. Corresponding individual-tree diameter growth rates are plotted in Figure 2. The

TABLE 1. Summary of calibration data.

Species group	Common name	No. of trees	Dbh (inches) Min.	Dbh (inches) Max.	Site index Min.	Site index Max.	Plot basal area(ft.^{2}/ac) Min.	Plot basal area(ft.^{2}/ac) Max.
1	White pine	1624	5	43	43	90	31	217
2	Eastern hemlock	1817	5	25	30	70	30	217
3	White spruce	468	5	22	31	70	33	180
4	Balsam fir	4036	5	18	30	70	30	209
5	Red spruce	4185	5	25	30	70	30	224
	Black spruce	255	5	17	30	65	36	158
6	Northern white cedar	2654	5	28	30	70	33	224
7	Quaking aspen	490	5	24	40	90	30	175
	Bigtooth aspen	246	5	20	40	86	31	180
	Balsam poplar	68	5	20	40	70	32	197
8	Black cherry	73	5	23	46	86	32	195
	American basswood	13	5	15	44	74	35	182
	White ash	260	5	27	40	86	31	198
	Black ash	101	5	15	40	86	37	224
9	Northern red oak	547	5	54	40	84	30	198
	Black oak	30	5	16	50	80	33	127
10	Paper birch	1528	5	23	40	80	31	198
	Gray birch	166	5	8	40	75	32	224
11	Yellow birch	1347	5	34	40	86	30	224
	Sweet birch	52	5	20	40	79	33	151
12	Sugar maple	1746	5	39	40	80	30	217
13	Red maple	2658	5	26	40	86	30	224
14	American beech	1409	5	26	40	80	30	198
	Total	25,773						

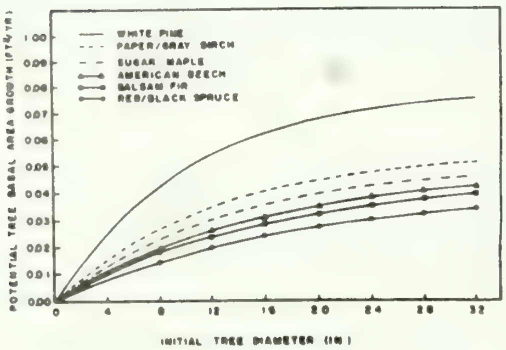

Figure 1. Potential tree basal-area growth rates (comparable to red spruce site index 50).

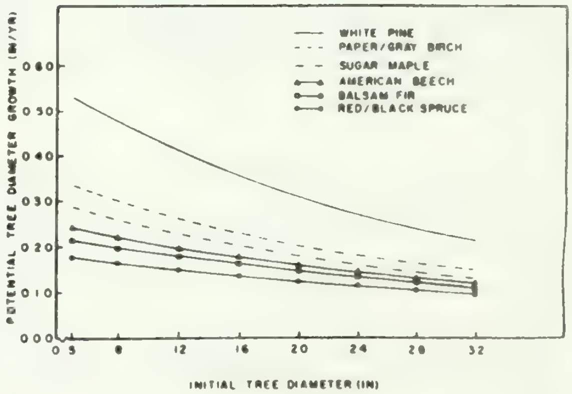

Figure 2. Potential tree diameter growth rates (comparable to red spruce site index 50).

asymptotic nature of equation (1) does not permit big trees to grow too fast.

MODIFIER FUNCTION

Scatter plots of the cell means revealed that individual-tree basal-area growth rates for all trees in a given dbh x site-index class declined in a negative exponential manner as BAL increased. This trend suggests the following model for a given dbh x site-index class:

$$BAG = POTBAG*(EXP(-b_3*BAL)) \qquad (2)$$

The intercept term, POTBAG, is the potential basal-area growth estimated from equation (1) for each dbh x site-index class. The equation is forced through the potential growth when BAL equals 0.

A two-stage modeling procedure was used to estimate the b_3's. An estimate of b_3 was determined by fitting equation (2) for each dbh x site-index class. The estimated b_3's were then plotted over dbh and site index to see if they could be modeled as a function of these two variables. No trends could be identified, so we used an overall average of b_3 for each species as our final estimate of b_3.

Prior to fitting equation (2) for each dbh x site-index class, an investigation of the error structure revealed that within-cell variances were correlated with dbh and BAL. The following model was fitted for each species to describe the error structure:

$$VARBAG = C_1*DBH*(EXP(-C_2*BAL)) \qquad (3)$$

where VARBAG is the variance of the individual-tree basal-area growth rates. Each observation was then weighted by the number of observations in the cell divided by VARBAG for the regression analysis used to fit equation (2) for each dbh X site-index class. Fitted values for c_1 and c_2 are shown in Table 2, and the resulting equation is plotted in Figure 3 for white pine.

Final estimates of b_3 and associated root mean square errors are listed in Table 2. The root mean square errors were calculated from individual-tree observations instead of cell means because it was no longer necessary to minimize the number of observations for modeling efficiency. Predicted individual- tree basal-area growth rates for white pine are shown in Figure 4 for a range of dbh and BAL values. Equation (2) imposes several constraints that we consider will probably be applied to nearly every imaginable set of standard conditions: (1) an individual tree's basal-area growth cannot exceed its potential growth--it equals the potential growth only when BAL=0;

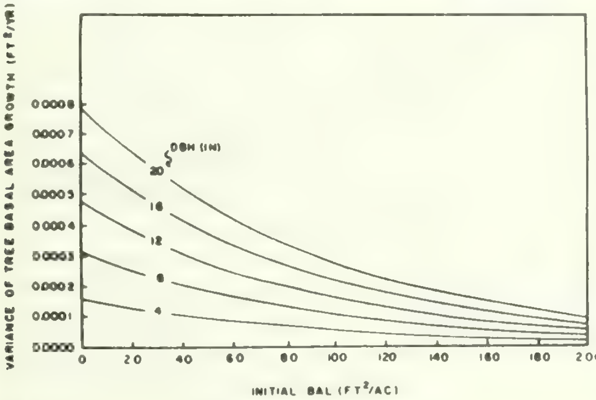

Figure 3. Variance of tree basal-area growth rates for white pine (site index 65).

TABLE 2. Individual-tree basal-area growth model coefficients and root mean square errors for calibration data.

Species[1/] group	Potential b_1	Potential b_2	Modifier b_3	Variance c_1	Variance c_2	Root mean[2/] square error
1	0.0012148	0.0965402	0.019136	0.0000393	0.0106664	0.017
2	.0011152	.0836339	.020732	.0000189	.0067648	.010
3	.0008721	.0578650	.013427	.0000155	.0173732	.009
4	.0008829	.0602785	.012785	.0000082	.0046624	.006
5	.0008236	.0549439	.011942	.0000084	.0048774	.007
6	.0009050	.0517297	.012329	.0000056	.0049320	.007
7	.0010834	.0949034	.024198	.0000133	.0049132	.011
8	.0010433	.0900725	.024975	.0000137	.0023253	.012
9	.0010382	.0879116	.023170	.0000131	.0049455	.014
10	.0009863	.0828333	.025111	.0000063	.0002953	.008
11	.0009863	.0770037	.018639	.0000171	.0077513	.011
12	.0009005	.0762029	.017540	.0000158	.0095937	.011
13	.0009005	.0731128	.018502	.0000198	.0127195	.009
14	.0008576	.0656505	.014751	.0000129	.0117606	.009

[1/] See Table 1 for species group definitions.

[2/] Root mean square error = SQRT ((Observed-Predicted)**2/n).

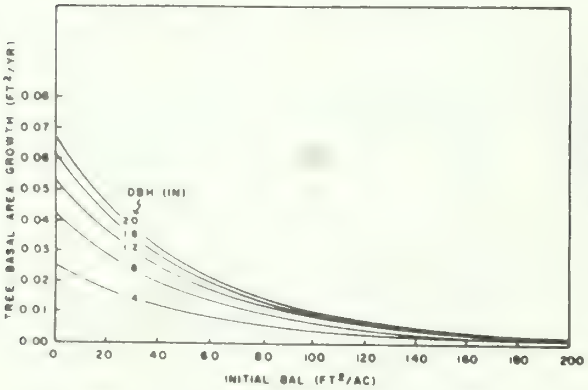

Figure 4. Predicted tree basal-area growth rates for white pine (site index 65).

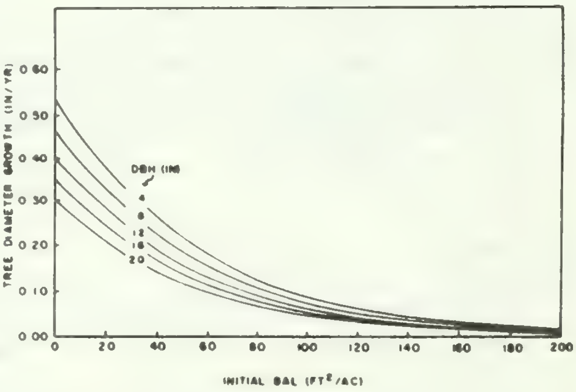

Figure 5. Predicted tree diameter growth rates for white pine (site index 65)

(2) individual-tree basal-area growth rates for a given dbh and site index decrease as BAL increases; and (3) as BAL increases, individual-tree basal-area growth rates for a given dbh and site index approach zero, but can never be negative.

Diameter growth rates corresponding to the basal-area growth rates for white pine are plotted in Figure 5. Individual-tree diameter growth rates (DGROW) are computed using equations (1), (2), and the following conversion formula:

$$DGROW = SQRT((DBH*DBH*C+BAG)/C)-DBH \tag{4}$$

where C = 0.00545415.

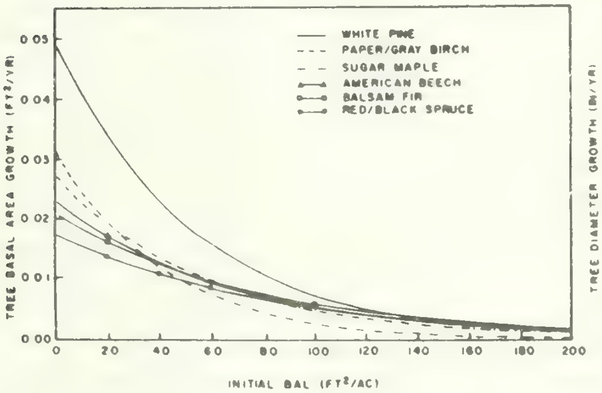

Figure 6. Predicted tree basal-area growth rates for a 10-inch dbh tree (comparable to red spruce site index 50).

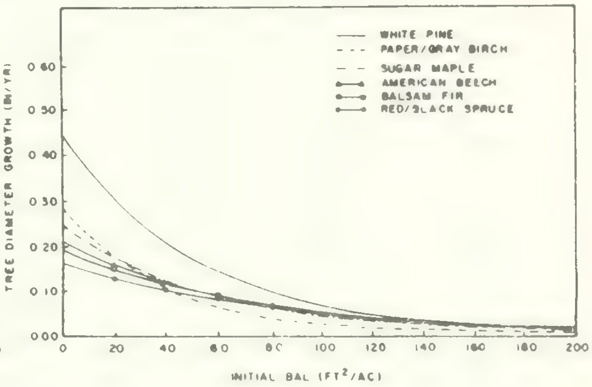

Figure 7. Predicted tree diameter growth rates for a 10-inch dbh tree (comparable to red spruce site index 50).

Individual-tree basal-area growth rates for several species are shown in Figure 6 for a 10-inch-dbh tree. Corresponding diameter growth rates are plotted in Figure 7. The crossing of the lines as BAL increases is indicative of various tolerance levels for the different species.

VALIDATION

Evaluation statistics for the validation data base are presented in Table 3. Validating a model for 11- to 13-year remeasurement intervals is difficult because we do not know when mortality and cut trees should be removed from the tree list. In actual application, the individual-tree diameter growth model would be linked with a mortality model for projecting future tree diameters. DBH and BAL would be updated annually for each 1-year projection after mortality trees have been removed from the tree list. Therefore, our validation statistics are based only on a 1-year projection using the initial tree and stand characteristics. Observed growth rates are simply the periodic annual growth rates for the remeasurement intervals.

TABLE 3. Comparison of observed and predicted growth rates for validation data base.

		Basal area (ft^2/tree)			Dbh (in/tree)		
Species[1/] group	No. of trees	Mean observed growth	Mean predicted error[2/]	Root mean square error[3/]	Mean observed growth	Mean predicted error[2/]	Root mean square error[3/]
1	228	0.0211	-0.0035	0.010	0.193	-0.037	0.090
2	494	.0135	- .0039	.007	.128	- .040	.067
3	97	.0122	- .0039	.007	.134	- .047	.074
4	976	.0080	- .0023	.004	.105	- .032	.057
5	1059	.0098	- .0031	.006	.107	- .036	.060
6	583	.0073	- .0018	.004	.078	- .022	.041
7	122	.0154	- .0013	.007	.186	- .019	.085
8	68	.0145	- .0022	.006	.138	- .023	.061
9	93	.0135	- .0024	.007	.136	- .031	.067
10	249	.0088	- .0018	.005	.104	- .023	.054
11	271	.0155	- .0032	.007	.134	- .032	.067
12	347	.0147	- .0031	.007	.135	- .033	.072
13	425	.0121	- .0031	.007	.132	- .037	.073
14	301	.0119	- .0035	.007	.126	- .040	.071
Total	5313						

[1/] See Table 1 for species group definitions.

[2/] Predicted minus observed growth. Negative values signify underpredictions.

[3/] Root mean square error = SQRT ((Observed - predicted)**2)/n).

The model appears to be underestimating growth consistently. Growth rates for most species are underestimated by approximately 15 to 30 percent. However, associated root mean square errors are fairly small for an individual-tree diameter growth model. Additional testing and examination of residuals after a mortality model is added to the simulator should reveal any serious bias in the model.

DISCUSSION

Developing reliable growth and yield models for the Northeast is important because this region is dominated by mixed-species stands with indeterminate age and size structures that have evolved from a multitude of past cutting practices. The model accounts for variation in growth due to species, dbh, site index, and BAL. Only three model coefficients were estimated--simple models are easier to adjust in the future if necessary. Also, the model form has constraints that should provide reasonable estimates of diameter growth when extrapolated beyond the range of the calibration data.

Individual-tree diameter growth models have limited value without corresponding individual-tree mortality models. And since only trees 5 inches dbh and larger were remeasured on northeastern forest survey plots, ingrowth models will also be an important component of stand growth. The entire growth projection system will be implemented via the TWIGS software programs (Belcher 1982).

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IMPROVING SINGLE-TREE DISTANCE-DEPENDENT GROWTH MODELS

Guy Larocque and Peter L. Marshall[1]

ABSTRACT. Single tree-distance dependent growth models can be improved in several ways. The greatest potential for improvement is in the way competition is modelled. New techniques based on a holistic approach to the competitive process are required. The development of such techniques depends on acquiring detailed data on the underlying processes. Detailed long-term data can also help reduce the variation which remains unexplained by the model. Less reliance on multiple linear regression techniques, and shortening the prediction periods should also improve the accuracy of single-tree distance-dependent models.

INTRODUCTION

Numerous single-tree distance-dependent growth models have been developed in the more than two decades since the pioneering work of Newnham (1964). Characteristics of this modelling approach have been discussed by many authors (Munro, 1974; Ek and Monserud, 1975; and Loucks et al., 1981, among others) and will not be reviewed here. Models based on this approach are generally flexible, and can be used to test and evaluate a range of management regimes. They are usually superior to models based on other approaches for examining various silvicultural options which result in irregular size distributions. However, data requirements for single-tree distance-dependent models are heavy, and the models tend to be complicated and expensive to run. This has led, in some cases, to the production of managed stand yield tables. While this allows a wide range of practitioners to access the results, it also limits the range of treatments which can be presented.

Considerable effort has been exerted on refining single-tree distance-dependent models in the last twenty years, and significant accomplishments have been made. A logical question to pose at this time is whether or not further refinements are possible, and if so, are they desirable.

We believe that significant improvements are both possible and desirable. Our observations are based on a detailed unpublished review of forest growth models by the senior author, comments in the literature, and our own experiences in modelling (principally with red pine [*Pinus resinosa* Ait.]). In the following sections, we introduce four major factors which we see as limiting the ability of single-tree distance-dependent models to predict tree and stand growth: (1) failure of competition indexes to incorporate sufficient biological detail to remain applicable over a wide

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range of stand conditions; (2) lack of good data representing a range of growing conditions; (3) large components of unexplained variation; and (4) reliance on a limited number of mathematical approaches.

INADEQUACIES OF COMPETITION INDEXES

The majority of competition indexes are based on the zone of influence concept that was developed by Staebler around 1950 (Gerrard, 1969) and first used in simulation by Newnham (1964). The major assumptions behind Newnham's use of competition in a tree growth model were: (1) a tree growing without competition is characterized by the diameter growth rate of an open-growth tree that has the same diameter; (2) diameter increment is reduced by an amount proportional to the competition it receives; and (3) mortality is related to a level of competition corresponding to a diameter growth rate that is less than a given threshold value. The diameter of the zone of influence of a tree growing in a stand is a function of the crown diameter of an open-grown tree of the same diameter. Modifications to this concept have included impact of competitor size on the subject tree (Daniels, 1976), and adjustment of the zone of influence based on certain physiological factors like shade tolerance (Bella, 1971).

The idea behind competition indexes is that it is possible to obtain a reasonable measure of the amount of resources that a tree cannot obtain because of the presence of competitors, and that levels of competition can be directly related to tree growth (Daniels et al., 1986). However, good measures of competition are not easy to develop because intertree competition is a very complex interaction (Munro, 1974; Daniels et al., 1986). Daniels et al. (1986) observed that the predictive ability of competition indexes varied with species, stage of development and cultural practices, and that no one index emerged as superior to the others. Numerous studies (Gerrard [1969], Bella [1971], Ker [1975], Daniels [1976], and Alemdag [1978], among others) have indicated that competition indexes do not seem to contribute much to growth prediction by themselves. However, more accurate growth predictions often are made when competition indexes are used in conjunction with DBH at the beginning of a prediction period.

These findings do not refute the idea that differing levels of competition affect growth. They only indicate that we cannot consistently estimate the quantity of competition present across a variety of stand conditions. A more thorough understanding of the biological mechanisms of competition is required. Such understanding will come through detailed studies of canopy and root system architecture, penetration of solar radiation, allocation of nutrients among trees of different competitive status, and mechanisms for translocation of resources within trees.

Studies of competition should look at the process in a holistic manner. Many studies of competition have concentrated on competition for light. A competition index based on light may not remain valid if either nutrients or moisture are limiting. Furthermore, a light-based competition index calibrated for a particular nutrient and moisture

regime may not be applicable if the nutrient or moisture regime varies, even if light continues to be the major factor determining growth rate.

The basic assumptions of Newnham (1964) with respect to competition have never been tested to the best of our knowledge. The usual procedure has been to apply them directly, and evaluate the predictive ability of the resultant model. Not only should these assumptions be tested, but alternate hypotheses should be formulated and tested. In addition, the effects of genetic variation on trees' ability to compete should be studied.

Most single tree-distance dependent growth models are designed to predict bole increment in terms of absolute growth rate (increase in size per unit time). Absolute growth rate may not be highly correlated with the degree of competition presently affecting the subject tree because it is influenced by the size of the tree. In other words, it is an indicator of past history, but not necessarily present competition (Ford 1979). Relative growth rate (the increase in size per unit size per unit time) may provide a more accurate measure of competition. Ford (1975, 1979, 1984) suggested that relative growth rate would be a very efficient way to assess competition within a stand because it is a direct measure of the change in efficiency caused by competitors. It also could reflect both the genetic potential of the tree and microsite conditions.

AVAILABILITY OF GROWTH INFORMATION

One of the major problems faced by modellers is lack of adequate growth information (Daniels et al., 1986). The majority of the models we examined could be characterized as being developed from relatively narrow ranges of age, site index, and stand density. Spacing trials and thinning experiments are very useful for calibrating models, but usually the results are only short-term. Accurate long-term remeasurement data on managed stands are scarce in North America.

This scarcity of adequate growth and yield data will be partially alleviated if existing studies in young managed stands continue to be maintained, and new studies are initiated. Agencies responsible for installing and maintaining permanent sample plots should be made fully aware of the value of their existing database, and the need for additional data to fill gaps. Often it is only the growth and yield researcher who fully appreciates the importance of good data covering the full range of current and anticipated management options.

There are many combinations of silvicultural treatments presently employed, and the future will see the introduction of many more treatments. Recent cooperative efforts in British Columbia, the Pacific Northwest region of the United States, and elsewhere in North America have shown considerable gains in efficiency from establishing cooperative databases. Regardless of the efficiency of the organizational structure established, it will be prohibitively expensive to install and maintain permanent sample plots to adequately cover all combinations of treatments, sites and species. Innovative designs are required to maximize the efficiency of any given database. Plots should be

strategically located in areas representing extremes of treatments and sites to include all potential responses. Detailed individual tree and stand measurements should be taken on each plot in anticipation of future information requirements.

UNEXPLAINED VARIATION

No model is capable of explaining all of the variation which occurs in a population of trees. Some variation is due to genetic and microsite variability among members of the population (Bella, 1970). Another portion is due to the model's simplified representation of biological processes. The remainder can be assumed to be due to random factors (e.g., endemic disease and insect infestations, climatic fluctuations, etc.) present in any dataset. Not enough is known at the present time to allocate unexplained variability among these different sources.

While it is impossible to totally remove the effect of random factors from data, steps can be taken to decrease their influence. Long-term records allow better determination of average impacts. Historic climatic records in conjunction with tree growth records may allow better correlations to be drawn between climatic fluctuations and tree growth. Research plots should be located in uniformly stocked, healthy stands to minimize the impact of incidental mortality. Model predictions can always be reduced by some factor when they are to be used to predict the growth or yield of actual stands. Operational standards and stand conditions will change from jurisdiction to jurisdiction, but the potential growth represented by a model may still remain valid.

The stochastic nature of individual tree growth and mortality could be reflected in the model. Some single-tree distance-dependent models already do this to some extent (e.g. Hatch [1971]; Keister and Tidwell [1975]). However, in order to accurately calibrate the distribution function, it is necessary to have detailed, long-term remeasurement data.

Better understanding of the biological processes associated with individual tree development will help reduce unexplained variation if this understanding can be accurately modelled. This will result in some complex models, and perhaps in heated debate on the value of complex models.

Models are, by definition, a simplification of reality. Simple growth models developed on aggregated datasets can sometimes predict stand level attributes more accurately than single-tree distance-dependent models because unexplained variation tends to average out over a stand. This has led to the widespread belief that simple whole stand models are more accurate than more complex single-tree models for predicting stand level characteristics. A number of comparisons have been made, but it is impossible to generalize the results of any specific comparison to all species and growth models.

We believe that growth models, in general, become initially less precise estimators of stand level attributes as they are made more detailed.

However, a point can be reached where sufficient biological detail is included that precision begins to increase, until ultimately, the precision of a stand level model is surpassed. Whether our present level of understanding is sufficient to do this, and whether it is worth doing at all, are debatable. However, we do not think that single-tree distance-dependent models should be considered inferior predictors of stand level variables simply by nature of the modelling approach.

MATHEMATICAL TECHNIQUES

Most single tree distance-dependent models are driven by multiple linear regression equations. Although the use of regression techniques is appropriate because they determine and evaluate the form of relationships, they do not explain the causal relationships between variables. Watt (1968) criticized the use of multiple linear regression equations in ecological modelling because biological systems are characterized by non-linear feedback systems. He stated that multiple linear regression constituted a useful tool only during the first steps of model development.

More effort should be directed towards developing process models. These are developed by describing and explaining the biological processes that relate the independent and dependent variables (Lieth, 1971; Leary, 1974; Hesketh and Jones, 1975; Hall and Day, 1977). The next generation of single tree-distance dependent growth models could focus on modelling intertree competition using mechanistic relationships.

The difficulty of reflecting competition with numerical indexes may be partially due to long projection periods. Ek and Monserud (1979) stated that competition is underestimated when predictions are made over long periods of time. Loucks et al. (1981) believed that shorter time steps can improve the accuracy of growth models. Shorter prediction periods would also permit a better simulation of the simultaneous occurrences of biotic interactions among the individuals in the population (Firbank and Watkinson, 1985).

In order to calibrate models with shorter prediction periods, it will be necessary to obtain very precise remeasurement data at frequent intervals (yearly?). This will greatly increase the expense of data collection over most operational permanent sample plot systems in North America which are remeasured much less frequently. Furthermore, it will be necessary to keep detailed records of climatic variation so that year-to-year fluctuations in growth rates due to climatic factors can be modelled. It may be possible to employ functional approaches, currently employed in some models of agricultural plant growth (Hunt, 1982), to reduce the frequency of measurements while retaining the advantages of shorter prediction periods.

Many single-tree distance-dependent models are evaluated entirely on the basis of the coefficient of determination. Although it provides a measure of the fit of the equations to the data, this statistic does not allow visualization of the behaviour of different state variables in relation to various conditions. There is no shortage of alternative methodologies (e.g. Reynolds et al., 1981; Reynolds, 1984; Reynolds and

Chung, 1986). Model builders should be aware of these techniques, and keep the information needs of the eventual user in mind when evaluating growth models.

CONCLUSIONS

It is time to step back from the traditional zone of influence concept, and examine other possibilities of quantifying competition. Future breakthroughs in single-tree distance-dependent models will likely require new ideas and innovative modelling approaches. Functional approaches and the use of relative growth rate were suggested as two possibilities, but many more undoubtedly exist.

We believe that the improvements suggested above are both desirable and possible in the near future. The biggest improvements should come through better understanding of the competition process. Incorporating this understanding into models will require detailed long-term observations of the full range of management strategies, and shorter projection periods.

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DEVELOPMENT OF A MIXED SPECIES PROJECTION SYSTEM FOR SOUTHERN FORESTS

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ABSTRACT. The development of growth projection systems for mixed species stands in the Southeast has lagged behind similar efforts in other areas of the country. This paper discusses the approaches and techniques used to develop a distance-independent, individual tree model using Forest Service survey data from Alabama, Georgia, and South Carolina. Models have been developed based on the following assumptions: 1) Forest Service survey data provide a reasonable representation of commercial forest stands occurring throughout the Southeast, 2) growth may differ among physiographic regions, e.g., Coastal Plain and Piedmont, and 3) growth may differ for a species among forest types, e.g., white oak in the oak-pine type and oak-gum-cypress type.

A brief description of the resource and data base is followed by a discussion of the stages of model development including crown ratio, diameter growth, height, and mortality. The use of cluster analysis to group species into like types is also examined.

INTRODUCTION

The initial stages of model development can be quite varied. One should consider the species, products, and region in question, the potential uses (users) of the model, data availability, and the various types of modeling methodologies. During this phase, one often has to realize the limitations of data bases, modeling methodologies, and numerous other aspects of developing a growth and yield projection system. It is not the purpose of this paper to dwell on the hurdles and pitfalls, but rather to present the procedure that is being followed to develop a projection system for the Southeast.

The importance of forestry to the South cannot be overstated. In many states, commercial timberland covers over 50 percent of the land area and has made the South a major producer of almost all forest products. Recent estimates indicate that the South accounted for one-third of the softwood lumber, over two-fifths of the hardwood lumber, close to half of all hardwood and softwood plywood, and two-thirds of the woodpulp produced nationally. In addition, the forests throughout this region provide wildlife habitat, watershed protection, and a range of outdoor recreation opportunities.

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The timberland which supports these activities are made up of a diversity of physiographic regions, forest types, and species. Many different physiographic regions exist in the South, and consist of such diverse regions as the Coastal Plains and the Blue Ridge Mountains, or the Piedmont and the Mississippi Delta. Forest types and acreages (millions of acres) are as follows: pine plantations 21.6, natural pine 40.5, mixed pine-hardwood 26.8, upland hardwood 62.5, and bottomland hardwood 30.1 (USDA 1987). Major species include loblolly pine, shortleaf pine, longleaf pine, slash pine, sweetgum, yellow poplar, cypress, various white and red oaks, and hickories.

The ownership of this forestland is also diverse, with the private non-industrial landowner being most prevalent. Ownership by category and acreages (millions of acres) are as follows: public 18.0, forest industry 42.1, and other private 121.5. Logically, the majority of pine plantations are found on land controlled by forest industry and the natural stands are found on private lands. In the past, growth and yield studies in the South have concentrated on pine plantations. This has created a paucity of information for the other 75% of forestland found in the South.

The purpose of the current research is to develop a growth projection system capable of modeling the development of major forest types throughout the South. Due to the complex structure of natural stands, the inherent flexibility of individual tree models, and the success of individual tree models in projecting mixed species growth and yield in other areas of the country, the selection of modeling methodology was rather simple. A distance-independent, individual tree model was the logical choice given our objectives. With the above information as background, the following discussion on the data base and model components will hopefully provide a chronology of the system development.

DATA

The only available data set which covers a reasonable geographic range and the predominant forest types of the region is U.S. Forest Service survey data. The USFS survey is an intensive inventory designed to provide information on a variety of forest and timber related parameters on an eight- to ten-year remeasurement cycle. The sample frame is a three-mile grid of cluster plots with a random start in each county. At each sampling location, a cluster of 37.5 basal area factor prism points are used to tally trees greater than five inches dbh (diameter breast height). Plot variables include stand origin, site class, age, forest type, etc. and tree variables include species, diameter, bole length, crown class, total height, etc. Fixed radius plots are established at a subset of the prism locations to obtain measurements on trees less than five inches dbh. Measurements on the fixed radius plots are similar to the variable radius plots except total height and height to the base of the live crown are not recorded. A more detailed description of Forest Service procedures is given by Quick (1980).

The data base for this project consisted of recent Forest Service survey data of Alabama, Georgia, and South Carolina, from the Southern and

Southeastern Forest Experiment Stations. As with most large sets of data, considerable time was spent examining the data and understanding variable definitions. This examination revealed several problems in using survey data, part of which were due to the combination of data from different experiment stations. Furthermore, due to the way Forest Survey must define particular variables, several key variables were not deemed very "reliable" (i.e., stand age and site class). Two other problems inherent in survey data also provided limitations. First, stand history is never completely known. Secondly, the sample design used was not an optimal design for the purposes of modeling growth and mortality. However, these weaknesses in the data were not viewed as severe enough to preclude the use of the data. Furthermore, no other data have been found which cover the numerous growing conditions found throughout the South.

Based upon this examination, past efforts, and discussions with other scientists, the following assumptions were established to initiate and guide the modeling process: 1) Forest Service survey data provide a reasonable representation of current conditions on commercial forest lands occurring throughout the Southeast, 2) individual species may grow differently in different physiographic regions, e.g., loblolly pine in the ridge and valley region vs loblolly pine in the flatland Coastal Plain, given identical stand conditions (age, site class, density, etc.), and 3) individual species may grow differently in different forest types, e.g., loblolly pine in the loblolly pine forest type vs loblolly pine in the oak-hickory forest type, given identical stand conditions (age, site class, density, etc.). Any or all of these assumptions may be argued; however it was felt that they provide a reasonable representation of tree and stand development.

CLUSTERING

Imposing the above assumptions on the data base resulted in a rather large three-dimensional matrix (physiographic region, forest type, and species) into which all sampling locations (trees) were classified. Many of the cells of this matrix were empty or had but few observations. The distribution of remeasurement trees for the major species (species groups) and forest types across physiographic regions is given in Table 1. The large number of cells and sparsity of data in most cells led to the development of a clustering procedure. This clustering procedure starts with the combination of cells until a minimum number of observations per cell is obtained (approximately 30 observations). The resulting groupings are considered to be the smallest clusterable units. This grouping is dependent on the researcher, and all attempts are made to group like types as much as possible (i.e., pine forest types, hardwood forest types). For manageability and additional control, grouping and final clustering is performed separately on pines, oaks, and non-oaks.

The implementation of the clustering procedure requires the user to define variable(s) on which to cluster, a weight (if desired), and the number of clusters desired. After extensive evaluation, it was determined that regression coefficients from simple linear models

Table 1. Distribution of Remeasurement Trees for Major Species and Forest Types across all Physiographic Regions.

Species FREQUENCY	Forest Type Slash Pine	Loblolly Pine	Shortleaf Pine	Oak-Pine	Oak-Hickory	Total
Slash Pine	3369	93	3	318	60	3843
Loblolly Pine	148	7515	280	2025	945	10913
Shortleaf Pine	19	1004	1475	1096	710	4323
Hickory	4	197	85	641	2556	3483
Sweetgum	117	1582	212	1451	2758	6120
Red Oaks	84	509	116	1159	2955	4823
White Oaks	130	719	172	1686	4127	6834
TOTAL	3871	11619	2343	8376	14111	40320

Total Number of Remeasured Trees = 82253

provided the best variables on which to cluster. For each of the smallest clusterable units, a simple linear model is fitted to relate an independent variable to the variable of interest. For example, when clustering for crown ratio, coefficients from the model crown ratio = b0 + b1 (Basal Area Bigger[2]) were used. The resulting coefficients for each of the smallest clusterable units are standardized and used as inputs for the clustering program, with the inverse of the significance level for the b1 coefficient used as a weight. The current clustering program being used is PROC FASTCLUS in SAS (SAS 1982).

The final number of clusters is determined using a statistic suggested by PROC FASTCLUS for the optimum number of clusters, by an imposed maximum number of clusters that can be practically implemented in the projection system, and by some final adjustments which are made by hand. For more detail on the clustering procedure and choice of clustering variables, see Meldahl et al. 1985.

MODEL DEVELOPMENT

Major model components include crown ratio, diameter growth, height growth, and mortality. For each component, the data are classified

[2] Basal Area Bigger is defined as the basal area/acre of trees greater than or equal to the dbh of the current tree.

and clustered as described above. That is to say, the clusters are not the same for all model components. This is a major change from other published efforts. It adds complexity to the system, but also allows flexibility that is not allowed in systems that assume that all components of a tree's development are simply related to its species. For example, white oaks in two timber types may grow the same in terms of diameter, but may have different patterns of crown ratio development (depending on physiographic location and forest type). A single implementation of clustering, usually done simply by species in most other studies, cannot capture these differences.

Several other departures from common model development also deserve comment. Initial efforts usually involve fitting published model forms or variations of them. In general, this has not been very rewarding and at times has been very frustrating. A second aspect which deserves note is the empirical nature of the majority of the models developed. Model selection is based upon the following: 1) fit statistics, 2) judicious use of independent variables, and 3) general robustness when models are applied to the validation data set (in most cases, 25% of the observations are withheld for validation). The resulting models are strongly influenced by the modeling data set and may not perform well outside the range of the data. This also represents a change from general practices, because many of the models are not biologically constrained or exhibit "bio-logic". As more data become available and as a better understanding of the diverse and complex relationships is achieved, the models will be updated and revised in future versions. Another aspect of this project is that the model form for any component does not have to be identical across all clusters, i.e., the loblolly pine crown ratio model may include different variables than the model for white oak. The purpose is to allow flexibility in order to reduce total unexplained variation (the sum of residual sums of squares across all clusters) for a component and still have a manageable number of model forms. In most other studies, all clusters (species groups) have the same model form for each component.

CROWN RATIO

Crown ratio is the first component to be modeled since its predicted value is used as an independent variable in other models. It is also the most difficult variable to model. Although estimates of crown ratio were provided as both a continuous variable and in crown ratio classes (10 percent classes), normal linear regression techniques are employed. In addition, since measurements of crown ratio were only available for the second measurement, a model was develeped to predict crown ratio given tree and stand characteristics rather than predicting the more preferable change in crown ratio. In the best cases, 40-50 percent of the variation is explained by the model, while in the worst cases only 5-10 percent of the variation is explained (however, the overall regressions were all significant). In all cases, the model is poor in predicting the extremes. Even though the model does not explain much of the inherent variation, in almost all cases, predicted crown ratio is very highly correlated with diameter growth. Most models currently are linear functions, and contain variables such as dbh, basal area/acre bigger than the current tree, site index, and number of trees/acre.

Considerable time has been expended trying to improve on the predictive ability of the crown ratio models. One method showing improvement for some clusters is the use of ordinal logistic regression. This extension of logistic regression allows the prediction into more than two categories, in this case crown ratio classes. The technique has been widely used in the medical field, but has seen little application in forestry. A more detailed description of the technique is given by Bolton et al. 1987.

DIAMETER GROWTH

The diameter growth model is the most important component of a projection system and has been given more attention than any of the other components. Due to limitations imposed by the sampling design, the approach to modeling diameter growth differed between trees ≥ 5 inches and trees < 5 inches in dbh. The basic approach taken for trees ≥ 5 inches has been to develop a potential growth function and then modify this estimate of potential growth to predict actual growth. For trees < 5 inches, a linear model has been developed for each cluster to predict actual diameter growth.

Due to the lack of open grown trees, the fastest growing trees and those trees which were growing with very little competition were examined for use in developing the potential growth function. Both diameter and basal area curves were explored with diameter curves being selected due to ease of application, better fit statistics, and less bias. Potential growth functions were then developed by species, or by a grouping of species, across all situations; forest types, physiographic regions, site classes, etc. These curves are based on a non-linear model and use the inverse of dbh as the independent variable. The modifier function was then developed by clusters. The modifier function converts a potential function on a regional level to a more local level and, in turn, models the local forest condition more accurately. These modifier functions are generally linear models, and include variables for site index, stand basal area, dbh, predicted crown ratio, and the number or trees/acre bigger than or equal to the current tree.

HEIGHT GROWTH

Due to limitations of the data set, height growth models are being developed in terms of bole length[3]. This was necessary since total height was not available for all trees or at both measurement times. The height growth model being currently developed is an empirically based regression model. Again, this is a definite limitation, but other alternatives were not available given the data set and the complexity of the resource. Many of the previously developed models rely heavily on variables such as site index and stand age. Unfortunately, due to the

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[3]Bole length is the length of a stem from a 1 ft. stump to a 4 in. d.o.b. (diamter outside bark).

complexity of mixed species forest types and uneven aged stand conditions, site index on an individual species basis is difficult if not impossible to determine. This correlation has been attempted for other regions, e.g., Carmean 1979, but to date, this information is not available for the South.

This also raises the question as to the form of the volume equations that can be implemented. If predicted bole length is the only available height measurement, standard volume equations, based on total or merchantable height to other than a 4 inch top, cannot be utilized. One would be restricted to use Forest Service volume equations or to develop other volume equations based on diameter and bole length. An alternative is to use Forest Service height equations to estimate total or sawlog heights. These estimates could then be used with ordinary volume equations.

MORTALITY

Mortality is the last component to be modeled. Logistic regression is the standard modeling technique. Most models are able to predict high probabilities of survival for individual trees that survived the measurement preiod, but have difficulty predicting high probabilities of mortality for many individual trees that did not survive the period. This is the general case and appears to reflect our inability to identify those measurable factors most closely related to individual tree mortality. This is confirmed whenever one plots survival against common tree and stand variables, i.e., density, crown ratio, etc. There are always individual trees that do not fit the general trend no matter how the data are sorted.

This problem is contrary to the -3/2 power rule and other self-thinning rules. However, it is an observable event in large data sets. Insects, disease, etc. can explain some observations, but in general we do not have a good handle on predicting individual tree mortality. The impacts of weak predictions can be smoothed somewhat by using the probability of mortality to reduce a trees expansion factor rather than as a zero-one event where an entire tree is removed from a projection.

SUMMARY

The models being developed will be implemented with regional volume equations in TWIGS (Belcher 1982). TWIGS is the latest version of an individual tree projection system developed in the Lake States. A Central States version is also available and a version for the Northeast is being developed. Current efforts for this project focus on deterministic growth projections, but the examination of error structures and a stochastic version are planned. Future enhancements also include finding and using additional data for validation and modeling, development of models to predict ingrowth and ongrowth, and expansion of the projection system to the other Southern States.

The development of a growth projection system for a large diverse area is a major undertaking. Concentrated efforts have been in progress in several areas of the country for numerous years. The task becomes a

never ending cycle of model and technique improvement, enhanced data bases, changing user needs, and increased computer capabilities. Unfortunately, in the end we are always one rotation behind new developments and state-of-the art management techniques. However, major strides are being made in developing a projection system which will fill in some of the gaps in growth and yield information in the South.

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A GENERALIZED COMPETITION INDEX FOR SRIC STANDS

Robert A. Merriam

ABSTRACT. Information on the effects of competition in short rotation, intensively cultured plantations has not been generalized into a useful planning framework. The author approached the problem by recognizing a maximum potential incremental growth. A real potential and an expected growth are derived from it. Real potential depends on a tree's size. The ratio of expected growth to real potential growth is estimated from a modified negative exponential equation. The equation is a function of the ratio of the growing space available to the growing space which the plant needs to achieve its potential growth. The equation is:

Growth ratio = [1 - exp(-k)(Space ratio)]**(1+m)

Information regarding growth potential and the growing space necessary for that growth are critical elements in SRIC plantation planning.

INTRODUCTION

To understand my approach to this paper you need to know that it is not a report of research results. Ten years ago this summer I was faced with preparing a legislative proposal for an Energy Tree Farm in Hawaii. The number of trees per acre to be planted was the single most important factor to be determined because of its effect on many different costs--cost of the nursery to be built, land cost, site preparation cost, as well as the cost of planting.

I expected to find guidelines in the literature that would let me apply what I knew about my potential species within a general framework of plantation spacing effects. Only a general range of values could be found. So, for planning purposes, I used an easy number; one thousand trees per acre. That was a compromise between the Hawaiian tradition and the extreme close spacings being studied by some planners of short rotation, intensively cultured (SRIC) plantations. This paper reports what I learned subsequently about spacing effects from an office-bound, data-free, theoretical standpoint. It has all the disadvantages, and I hope some of the advantages, of such a report.

I deal with competition effects on incremental (normally annual) growth. I look at differences among average trees in SRIC stands planted at different spacings. This is not a within-stand competition study. Although I speak of individual trees, each tree represents the average tree of a stand, whatever the size of that stand.

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My purpose was to understand spacing effects on growth, not to build a model. I have always believed that models are more important for the questions they ask, than for the answers they give. I cannot tell you how your trees will grow. But if you can answer: 1) How fast will your trees grow on your site if they are free of competition? and 2) How much growing space do they need to reach that growth?, then 3) I will give you a way to evaluate the trade-offs between individual size and total volume per unit area.

COMPETITION AND GROWTH

"Competition exists if the site resources available to the individual are reduced and the development of the individual is modified by the presence of other individuals of the population" (Curtis 1970).

Development of the individual, or growth, needs to be considered in several distinct, but related ways; as incremental growth and as accumulated growth of the individual trees as well as the cumulative effect of that growth in the stand. Two basic concepts regarding the incremental growth of an individual tree can be expressed as follows:

1) On a given site, at any stage in the life of a tree of specific genetic makeup and condition, there is a growing space which will permit that tree to grow to the limits of its potential. I use the term 'competition threshold space' (CTS) to describe that growing space. The term 'threshold density' was used to define the number of trees per unit area at which competition begins by Adlard (1981).

2) Additional space per tree does not result in increased growth of individuals. Less space does result in reduced growth of individuals.

A tree which has developed in a forest stand, but which has been free of competition throughout its life, is clearly a 'premium' tree. I call any other tree, smaller by definition, an 'object' tree.

STAGES OF PLANT GROWTH

I find the following distinction among plant growth stages helpful. When a tree is planted, it has enough room to grow unhindered for some period, however short. That period may be called the Pre-competition Growth Stage. There is mortality from planting stress, but other trees reach their growth potential and production per unit area is directly proportional to the number of trees.

In the early years of competitive growth there is another period with several characteristics which are distinctly pertinent to SRIC management. In the Density-dependent Growth Stage, growth is affected by density, but there is not yet any competition-induced mortality. A reduction in the growth rate of the individual trees subject to competition occurs. There may be a change in the distribution of growth among the trees' parts, described by Harper (1977) as the 'plastic' response to stress. Mortality due to planting stress ends during this

period, and mortality of twigs and branches on otherwise healthy trees begins. Stands are still uniform and the average tree is still a good indicator of stand condition. When stands of the same age but different densities are compared, stands with more trees have smaller trees but there is more growth per unit area on the crowded stands. The density-dependent stage is particularly important in SRIC plantations since it may represent a major part of the tree's life.

After that early period of competitive growth, competition-induced mortality starts. That is the beginning of the Mortality-dependent Growth Stage, essentially what has been called the 'self-thinning' stage by others. I use 'mortality-dependent' because this stage may include planned management thinnings as well as natural mortality. In terms of the effect on the remaining trees, it matters little whether the trees died naturally or by the chainsaw. Volume loss due to competition begins to be dominated by the mortality of whole trees rather than the shedding of minor tree parts. The growing space available to each tree is more determined by what happens to the tree's neighbors than the space it had at planting. The remaining trees are capable of rapidly taking advantage of any space available to them. As a result, size differences among trees become more pronounced and by the end of the period, the 'average' tree is less reliable as an indicator of stand conditions. Thinned stands are an exception because management thinning usually reduces size variation.

SRIC plantations probably will reach neither the Site-dependent Growth Stage, during which 'all stands tend toward normality', nor the final Age-dependent Growth Stage in which the remaining trees are not able to take advantage of extra space due to mortality, from old age, of others.

The duration of each growth stage is initially very dependent upon the growing space allotted to each tree at the time of planting. Later it becomes dependent upon mortality. With adequate growth records, such as free growth (Robinson 1968) and correllated curve trend studies (Pienaar and Turnbull 1973), the boundary between the pre-competition and density-dependent stages can be determined. It is that time when growth of the individuals in the closer spacing is less than that in wide spacings. The boundaries between the density-dependent, mortality-dependent and the age-dependent stages are less distinct. Lack of clear definition, however, does not mean that the stages are not different in important ways or that their distinction is not useful for discussion.

I do not pretend that these ideas are radical or new. Most of them have been proclaimed by others more eloquent than I. Although growing space suggests physical limits to growth, the critical space may be no more than the 'container' for one or more of the many resources which the tree actually requires.

Given those caveats and the fact that I will continue to use the word 'growth' in a very general way, I am going to restate the ideas above into a simple mathematical expression.

A GENERALIZED COMPETITION INDEX

Intraspecific competition among forest trees includes two very distinct factors which affect an individual's future growth. First is the size of the tree, the carry-over effect of past competition. Size, among otherwise similar trees, is the single most important characteristic related to future growth (Perry 1985). Secondly there is the direct competition for future growth needs expressed by the other trees in the stand (Curtis 1970, Perry 1985). The initial assumption in this paper is that SRIC trees interact equally and competition within a stand is uniform. Competition differs among stands of different spacings.

FUTURE COMPETITION

Although many competition indices had been developed, ten years ago I was unable to find one which was based on general principles, which was simple, and which was suitable for comparisons among SRIC stands. The situation today is not much clearer.

I start from a basic premise of ecological growth modeling (e.g., Reed 1980) as stated by Holdaway (1984) "...the growth of a tree is the product of its potential growth and a modifier of that potential due to competition...". The modifier I propose is similar to Holdaway's in basic form, although much simpler. (The opportunity for simplicity comes from the uniform young stands with which I deal.) The generalized equation for the modifier is:

$$\text{Growth Ratio} = [1-\exp(-k)(\text{Space Ratio})]^{**}(1+m) \quad (1)$$

where growth ratio is the ratio of the growth expectation of an individual tree to the growth potential of that tree. The modifier expresses the effects of future competition as a ratio of the likely to the possible growth. Space ratio is the ratio of the amount of space a tree has to its competition threshold space. Parameters k and m will be discussed later.

When a premium tree encounters competition for the first time, its growth expectation (PTGE) will be reduced from its growth potential (PTGP) by the modifier of equation (2).

$$PTGE/PTGP = [1-\exp(-k)(PTAS/PTTS)]^{**}(1+m) \quad (2)$$

where (PTAS) is the premium tree's available space and (PTTS) is its competition threshold space.

Any tree smaller than a premium tree will have a growth expectation (OTGE) related to its growth potential (OTGP) by equation (3).

$$OTGE/OTGP = [1-\exp(-k)(OTAS/OTTS)]^{**}(1+m) \quad (3)$$

where (OTAS) and (OTTS) are available and threshold space respectively.

The rationale for the use of the negative exponential equation for growth response curve has been given many times (e.g., Assmann 1970, Currah 1974, Reed et al. 1983). Mitscherlich had proposed that his model relating plant weight with growth factors could be applied to growing space (Currah 1974). Currah conducted such an analysis in the form of yield per unit area as a function of the number of plants. Reed et al. (1983) report the interaction of negative exponential expressions with other growth factors. Unfortunately the English translation of Assmann's (1970) otherwise important work confuses natural and base 10 logarithms and is partially incorrect.

In my equation the exponent 1+m, where m is a small non-negative number, provides shape flexibility to a family of curves, (Grosenbaugh 1965). These curves vary from the negative exponential when m=0 to the mathematical equivalence of the Gompertz equation at large values of m. The curve is von Bertalanffy's equation when m=2. Although my equation is mathematically like the Chapman-Richards modification of the von Bertalanffy equation (Pienaar and Turnbull 1973), the basic derivation is not similar. Time is not a parameter in the expression used here. The exponent 1+m is much more likely to be near 1 than 3. Therefore I prefer to use the term 'modified negative exponential' or 'modified Mitscherlich' for these curves.

If a growth ratio of 0.99 is accepted as the 'saturation point' for growth, the values of either k or m can be determined when an assumed value is used for the other. For example when m=0, k=4.605 at the point where the space ratio equals 1. This equation is equivalent to that for photosynthetic efficiency of Perry (1984) for the species which followed the c=1 curve within his family of Wiebull curves. A premium tree, with adequate space to grow to its fullest potential is essentially equivalent to Perry's tree which is fully exposed, so that photosynthetic production is maximized.

When m=0.1 and k=4.700, the difference in the modifier is small. The sigmoid characteristic of the curves which a small value of m produces results in more reasonable modifier values as we shall see later.

These equations bring the basic work of Mitscherlich in the the 'modern world' of growth curves. His basic concept of a limiting value is intact and the addition of another parameter adds flexibility which was not available with the basic formulation.

PAST COMPETITION

The dominant factor in trying to estimate the future growth of a tree is its size (Perry 1985). A simple reflection of the effects of past competition can be derived from the unmet growth potential. The size modifier (ZMOD) is the ratio of the size of the object tree (OTZ) to the size of a premium tree (PTZ).

$$ZMOD = OTZ/PTZ \qquad (4)$$

Growth potential of an object tree (OTGP) can now be expressed in terms of the growth potential of a premium tree (PTGP).

$$OTGP = ZMOD * PTGP \qquad (5)$$

Equation (5) predicts the obvious; the closer a tree is to the size of a premium tree, the closer its growth potential comes to the growth potential of a premium tree.

As a first approximation, I also use ZMOD to reduce the space needed for future growth. An object tree's threshold space (OTTS) is derived from a premium tree's threshold space (PTTS), by equation (6).

$$OTTS = ZMOD * PTTS \qquad (6)$$

THE INDEX EQUATION

The index may now be written in completely generalized form as:

$$OTGE/((OTZ/PTZ)*PTGP) = [1-\exp(-k)(OTAS/((OTZ/PTZ)*PTTS))]**(1+m) \qquad (7)$$

Since the parameters k and m are derived from reasonable assumptions, independent of the rest of the data, the generalized equation requires only the following information: 1) the past and future growth potential of a premium tree, 2) the growing space necessary for that growth, and 3) the size of, and the growing space available to, the object tree.

GROWTH PER UNIT AREA IN STANDS

With premium trees, the largest trees which can fully utilize the site, the growth per unit area (GAPT) is equal to the number of premium trees (PTNA) times the expected growth of premium trees (PTGE), or

$$GAPT = PTNA * PTGE \qquad (8)$$

Growth on a stand of object trees (GAOT) is the product of the number of object trees (OTNA) and their growth expectation (OTGE), or

$$GAOT = OTNA * OTGE \qquad (9)$$

As the number of object trees becomes very large, the corresponding growing space becomes very small. l'Hospital's Rule can be applied to the equation for the growth per unit area of the maximum number (each with minimum space) of object trees. When appropriate substitutions are made in the case of $m=0$, the coefficient k is found to represent the ratio between the maximum growth per unit area on very small and crowded trees and the growth on the same area if that growth is put on premium trees, or

$$GAOT/GAPT = k \qquad (10)$$

For the case of m not equal to zero, the ratio is always less than k.

The classic study of Ek and Dawson (1976) was used to estimate 'k' ratios of 3.65, 4.05, and 3.14 for ages 2, 3, and 4. At age 2 the nearest value to CTS was the 4.0 sq ft spacing. At ages 3 and 4, the spacing nearest CTS was 16 and 64 sq ft, respectively. Thus the yield ratio was nearly constant although the space ratio varied from about 1:7 to over 1:100 during the three years. The few other studies found with a wide range of growing spaces support the order of magnitude of k.

DISCUSSION

There appear to be two reason why growing space has not previously been put in the negative exponential framework suggested by Mitscherlich. The first is the concept of normalizing space in the form of the ratio of an actual to a needed value. This form permits a derivation of the rate constant, k, independent of the actual growing space.

Secondly, growing space has an apparent difference from other growth factors. When the trees in one stand have more fertility than their counterparts in another, they respond with increased individual growth and increased growth per acre. When trees in one stand have more space than those in another, individuals grow more, but because there are fewer of them, growth per acre is less.

Use of the generalized equation assumes that maximum growth will occur on a tree free of competition. That is likely true for the part of a tree's life of concern to SRIC plantations. An object tree with adequate space will grow less than a premium tree because of its reduced size. With less space, its growth will be further reduced.

The growth of a forest stand depends upon the number of individuals and the growth of those individuals. Up to some point, more trees result in more growth. After that point there can be a large increase in the number of trees without significant change in the total production per unit area. With too many individuals, however, the number of plants may be great enough to cause reduced growth per unit area.

Since the relation between growth per unit area and the growth of a premium tree has been established, it is now apparent that the premium tree concept is important to this analysis in a theoretical sense. It is likely that young open-grown trees will be indistinguishable from trees grown in a stand. However, the concept of stand-grown trees as a standard is valuable and specific differences between stand- and open-grown trees may be found even at an early age.

Most SRIC plantations are treated today as basic units. I have tried to look beyond that into the behavior of individuals within the stand as they are collectively affected by each other. Each tree has a potential for growth and a requirement for space to achieve that growth. I suggest that if we do not know the growth potential of individual trees, and if we do not know at what point each tree begins to affect if neighbors, we cannot possibly be effective managers of that collection of individuals we call a stand.

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TREE HEIGHT CHARACTERIZATION IN UNEVEN-AGED FOREST STANDS

Paul A. Murphy and Robert M. Farrar, Jr.[1]

ABSTRACT. Using the analog of dominant stand height from even-aged models, a height projection model is developed employing the tree of maximum diameter in uneven-aged loblolly-shortleaf pine (*Pinus taeda* L.--*P. echinata* Mill.) stands. Heights of trees in lower diameter classes are derived as a function of their diameter, the maximum diameter, and the height of the tree of maximum diameter. This model can be applied to any growth and yield system that produces a stand table.

INTRODUCTION

There have been considerable advances in uneven-aged growth and yield prediction methodology since the development of earlier stand-level models. Now--through stand table projection, individual-tree, and size-class distribution models--one can project uneven-aged stand development by diameter classes or by individual trees through time. However, an important component needs further refinement--the modeling of tree heights and their development. Only two innovative attempts have been made for uneven-aged stands. One is by Stage (1975) in which he predicted height increment of individual trees as a function of their height, diameter, diameter increment, and other variables. The second is the model "FOREST" by Ek and Monserud (1974) in which they used a multiplier that modifies potential height growth; the potential growth is derived from a site index equation. Both approaches utilize tree list information that includes individual tree heights. Other techniques are basically an adaptation of height-given-diameter equations.

Having to furnish the height of all trees is very time consuming and data demanding. A technique in which a sample of tree heights is used and that performs better than a simple height-diameter equation merits development. Another requirement is a model that can be used with either individual tree- or size-class distribution models. If estimates of tree heights and their development are available, tree taper or stem profile functions can be used to produce stock tables. Users are not then restricted to arbitrary merchantability standards.

The purpose of this study was to develop models for the prediction of tree heights in uneven-aged stands and their development through time.

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DATA

The data came from permanent 0.2-acre inventory plots maintained on forest industry land[2] in southeast Arkansas in uneven-aged loblolly-shortleaf pine (*Pinus taeda* L.--*P. echinata* Mill.) stands. Measurements were conducted in 1966, 1971, and 1976. Individual information was maintained for all trees 5.0 inches and larger. Pertinent information for this analysis included (1) species, (2) dbh to the nearest 0.1 inch, (3) height from stump to tree tip, (4) tree history, (5) stump height, and (6) tree product class. Observations of plots that were cut during a growth period, that had basal areas containing less that 50 percent shortleaf or loblolly pines, or that had apparent measurement discrepancies were not used. Most growth periods were 5 years, but a few were 10 years in length. The number of plot growth observations retained for analysis was 103.

The following information was extracted for all shortleaf and loblolly pines: the total height of the maximum diameter tree at the start and end of the growth period ($H_{Dmax,1}$ and $H_{Dmax,2}$) and the diameters (d_i) and total heights (h_i) of all trees at the start and end of each growth period. Total heights were calculated by adding stump height to the recorded height from stump to bud tip.

MODEL DEVELOPMENT

HEIGHT PROJECTION OF LARGEST TREE

The height of the dominant and codominant trees (dominant stand height) has been the predominant measure of stand height for predictive purposes in even-aged southern pine stands. Stand height development is projected over time by using site index curves. Heights of trees in individual diameter classes are predicted as functions of dbh, dominant stand height, and other variables. The success of this method depends upon how accurately the site index curves portray height growth of the dominant stand.

This technique cannot be applied to uneven-aged stands because even-aged crown classes do not apply, and dominant stand height is not defined. One might consider an uneven-aged loblolly-shortleaf pine stand to be composed of small even-aged clumps of trees. A dominant tree in one clump might be quite old and large, but in a patch of reproduction the dominant tree might be only a few feet in height. The result would be a highly variable and imprecise estimate of dominant stand height. Moreover, the use of site index curves for projection may have limited applicability in this context.

However, the dominant stand concept might be adapted for uneven-aged stands. The dominant and codominant portion of an even-aged stand contains the tallest trees. Likewise, one wants to choose an uneven-aged height component analogous to the even-aged one. Traditional

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[2]We thank Dr. Bill Pope and Mr. Jerry Coffman, Potlatch Corporation, Warren, AR, for kindly providing these data.

uneven-aged regulation methods (Brender 1973, Farrar 1984, Marquis 1978, Moser 1976, Murphy and Farrar 1982) have used three variables: residual basal area, q (a measure of structure--the ratio of numbers of trees in adjacent diameter classes), and maximum diameter. The tree of maximum diameter is the largest one that is to be left to grow, and its chosen size is based upon both silvicultural and economic factors. For modeling purposes, a reasonable assumption to make is that the maximum diameter tree is also likely to be the tallest one. Furthermore, if the height of this tree is known, it is assumed that the height of the smaller trees can be modeled as a function of its height. Finally, if the height development can be described over time for the tree of maximum diameter, it is assumed that future heights of smaller trees can also be predicted from this development trend.

Annual tree height growth at first increases, culminates at a rather early age, and then declines. Trees of maximum diameter in uneven-aged stands are past the age of height growth culmination. Therefore, the function that describes height growth of the maximum diameter tree will be monotonically decreasing with time. The following function fits this description:

$$dH_{Dmax}/dt = a_1 \exp(a_2 H_{Dmax}), \tag{1}$$

where

dH_{Dmax}/dt = change of H_{Dmax} over time,
a_i = coefficients to be estimated,
exp = the base of the natural logarithm,

and the other terms are as previously defined. Equation (1) will be strictly decreasing if $a_2<0$ and $a_1>0$. Since we are ultimately interested in future height rather than growth, we shall integrate equation (1) to derive an equation for projected height. Temporarily, we redefine dt as ds,

$$\exp(-a_2)dH_{Dmax} = a_1 ds,$$

$$\left[- \exp(-a_2 H_{Dmax})/a_2\right]_{H_{Dmax,1}}^{H_{Dmax,2}} = \left[a_1 s\right]_0^t,$$

$$[\exp(-a_2 H_{Dmax,1}) - \exp(-a_2 H_{Dmax,2})] = a_1 t.$$

Rearranging terms, the result is

$$H_{Dmax,2} = -\ln\{\exp[-a_2 H_{Dmax,1}] - a_1 a_2 t\}/a_2.$$

Reparameterizing with $k_1=-a_2$ and $k_2=-a_1 a_2$, the result is

$$H_{Dmax,2} = \ln\{\exp[k_1 H_{Dmax,1}] + k_2 t\}/k_1, \tag{2}$$

where

$H_{Dmax,1}$ = initial total height, in feet, of tree of maximum diameter,
$H_{Dmax,2}$ = height, in feet, of tree of maximum diameter in t years,
t = elapsed time in years, and
k_i = coefficients to be estimated.

Although equation (2) does not have a site quality variable, one could be added to it by first working with the differential form and hypothesizing how site might affect height growth.

The 103 growth observations (Table 1) were used to fit equation (2). The coefficients were estimated using derivative-free nonlinear regression (SAS Institute, Inc. 1985).

TABLE 1. Summary of data used in height projection of maximum diameter tree as based on 103 observations.

Variable	Mean	Standard deviation	Range
		---feet---	
$H_{Dmax,1}$	68.9	12.9	43-103
$H_{Dmax,2}$	75.4	11.8	51-104
		---years---	
t	5.8	1.8	5-10

The resulting equation is

$$H_{Dmax,2} = \ln\{\exp[0.023528\ H_{Dmax,1}] + 0.14197\ t\}/0.023528, \quad (3)$$

$$RMSE=2.6 \text{ feet}, \quad I^2=0.95,$$

where

RMSE = root mean square of the residuals,
$I^2 = 1 - \Sigma(y_i - \hat{y}_i)^2 / \Sigma(y_i - \bar{y})^2$,
y_i = observed value,
$\hat{y}_i$ = predicted value, and
$\bar{y}$ = mean value.

The fit appears to be good, and no trends were observed when residuals were plotted. Therefore, equation (2) was deemed acceptable as a model for height development of the maximum diameter tree for uneven-aged loblolly-shortleaf pine stands.

INDIVIDUAL TREE HEIGHTS

The following equation represents a height-diameter relationship that has been widely used:

$$\ln(h_i) = b_0 + b_1/d_i, \quad (4)$$

where

h_i = total height of ith tree, in feet,
d_i = diameter at breast height of ith tree, in inches, and
b_j = coefficients to be estimated.

Taking the difference between the ith tree and the tree of maximum diameter and exponentiating both sides, we obtain the following relationship:

$$h_i = H_{Dmax} \exp[b_1(1/d_i - 1/Dmax)]. \quad (5)$$

The coefficients for equation (5) were estimated from 4,853 individual tree observations in the 103 plot observations using derivative-free nonlinear regression. As observed in the data (Table 2), trees with smaller diameters can be taller than the tree of maximum diameter. The robustness of our assumption that the tree of maximum diameter is also the tallest tree, or its height is close to that of the tallest tree, will be corroborated by the fit of the individual tree height equation. As an additional confirmation, equation (4) was also fitted to enable us to judge the performance of equation (5). Where appropriate, predicted values of H_{Dmax} from equation (3) were substituted for observed values in the subsequent fitting of equations for h_i.

TABLE 2. Summary of data used in individual tree height projection analysis as based on 4,853 observations.

Variable	Mean	Standard deviation	Range
		feet	
h_i	51.8	13.6	12.5-108
H_{Dmax}	9.3	11.3	43.0-104
		inches	
d_i	8.6	3.4	5.0-26.6
Dmax	16.2	3.4	10.2-26.6

The resulting equations are

$$h_i = \exp(4.6234 - 5.3338/d_i), \tag{6}$$

$$\text{RMSE}=8.0, \; I^2=0.66.$$

$$h_i = H_{Dmax} \exp[-4.8315(1/d_i - 1/Dmax)], \tag{7}$$

$$\text{RMSE}=7.7, \; I^2=0.68.$$

The results indicate that equation (7) is some improvement over using a height-diameter equation. However, equation (7) showed trends in the residuals. After plotting the residuals against several independent variables, it appeared that the trends were related to H_{Dmax}. Thus, equation (7) was incompletely specified, and it needed to be augmented by or with some function of H_{Dmax}. The following alternative functions were tested:

$$h_i = H_{Dmax} \exp[b_1(1/d_i - 1/Dmax)]\{H_{Dmax}\}^{b_2(1/d_i - 1/Dmax)}, \tag{8}$$

$$h_i = H_{Dmax} \exp[b_1(d_i^{b_3} - Dmax^{b_3})]\{H_{Dmax}\}^{b_2(d_i^{b_3} - Dmax^{b_3})}, \tag{9}$$

$$h_i = H_{Dmax} \exp[b_1(d_i^{b_3} - Dmax^{b_3})]\{H_{Dmax}\}^{b_2(d_i^{b_4} - Dmax^{b_4})}. \tag{10}$$

Equations (8), (9), and (10) were also fitted with derivative-free nonlinear regression.

TABLE 3. Regression results from adding a function of H_{Dmax} as an additional variable.

Estimate	Equation		
	(8)	(9)	(10)
Coefficients:			
b_1	22.284	68.487	48.221
b_2	-6.3481	16.704	-5.1918
b_3	-	0.0033141	-0.050505
b_4	-	-	-0.21264
RMSE	6.9	6.8	6.8
I^2	0.74	0.75	0.75

All the revised equations--(8), (9), and (10)--showed a significant improvement over equation (7) (Table 3). Equations (9) and (10) performed marginally better than equation (8). But there is not much difference in the fit statistics of the three equations, and equation (8) might be preferred because of its simpler form. Moreover, some minor convergence problems were encountered in fitting equations (9) and (10).

APPLICATION

As an example, suppose that a selection stand contains a maximum diameter tree of 15.0 inches with a height of 70 feet. In the locality, such trees commonly grow 2 inches in diameter in 5 years, so its future diameter will be 17.0 inches. Using equation (3), its projected height would be 75.4 feet.

Using the current height, 70 feet, of the tree of maximum diameter and its diameter, we can obtain the tree heights for the smaller diameter classes of the current stand using equation (8) (Table 4). In 5 years the maximum diameter tree will have grown to 17 inches dbh and 75.4 feet in total height. Again using equation (8), we can derive the heights by diameter class for the future stand in 5 years (Table 4).

Notice the trends in the heights by diameter classes. In the projected stand, the smaller diameter classes have shorter heights than equivalent classes in the current stand. In the intermediate diameters, the heights are nearly equal. In the larger diameters, the projected stand has taller trees per diameter class. This trend has also been observed in the heights predicted for some unthinned stands of even-aged southern pine (Dell and others 1979, Feduccia and others 1979, Farrar 1985). It appears to be reasonable and apparently is due to differential development of height with respect to diameter and time as trees pass through diameter classes. As time passes for a given stand, the net

effect seems to be that trees in the smaller diameter classes are retarded somewhat in height development, and those in the larger classes accelerate slightly in height growth. Thus, at two different points in time a given diameter class may not have the same height. For example, the small class (e.g., 4 inches) will likely have less future height growth than initially, and a large class (e.g., 18 inches) is likely to have more future height growth than initially. However, the validity of these trends for uneven-aged stands will bear further verification through additional research.

TABLE 4. Current and projected tree heights in 5 years of an uneven-aged loblolly-shortleaf pine stand with an initial maximum diameter of 15 inches.

Diameter	Predicted tree heights by diameter class	
	Current[a]	Projected[b]
---inches---	---feet---	
5	37	36
6	44	43
7	49	49
8	53	54
9	57	58
10	60	61
11	62	64
12	65	66
13	67	69
14	68	71
15	70	72
16	-	74
17	-	75

[a]Tree heights were predicted by equation (8) using current $H_{Dmax}=70$.

[b]Tree heights were predicted by equation (8) using projected $H_{Dmax}=75.4$ in 5 years.

CONCLUSION

The height development of the tree of maximum diameter in uneven-aged loblolly-shortleaf pine stands can be adequately predicted, and heights of smaller diameter trees can be derived as a function of their diameter, the maximum diameter, and the height of the tree of maximum diameter. The equations were developed from data of limited conditions and do not represent operational models. Potential users are advised to use their own data to fit these models.

Using these models, the heights of the projected stand are apparently shorter in the lower diameters, equal in the intermediate diameters, and taller in the larger diameters than the heights of the original stand.

Whether this actually occurs, and the effect of this phenomenon upon predicted heights during repeated simulation when these models are incorporated into a growth and yield model, needs further investigation.

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TREE GROWTH PROJECTION BASED ON PARAMETERS MEASURED ON AERIAL PHOTOS

Jürgen Nagel and Alparslan Akca[1]

ABSTRACT. Individual tree growth projection systems have proven to be superior to simple stand growth models for management purposes. They require, however, more detailed and more expensive information from single trees. In order to minimize cost and to use old data data sets, some models provide data generators which give estimates for missing height, crown and other measurements.

Modern photogrammetric methods allow the measurements of height and crown parameters on large scale aerial photos with a comparable precision to terrestrial techniques. Because the measurements of tree parameters on aerial photos are less cost effective than those taken on the ground, it is possible to provide more data for growth models with a given budget. Aerial photos are an important source for documentation of forest lands and measurements can be repeated at any time, even after years.

The quality of tree parameters measured on aerial photos is equal to that of the parameters measured in ground inventories. The estimation of the volume increment using a regression model with aerial parameters is nearly as good as using a regression model with ground parameters. The aerial photo measurements are less costly than the ground measurements.

INTRODUCTION

The knowledge about tree growth is one of the most important factors in the effort of securing a sustainable yield of all benefits from forest ecosystems to society. For over one hundred years German foresters have observed the growth of forest stands and developed yield tables from these observations to forecast the growth. Today these yield tables are an important source of information for managing the forests in Germany.

In recent years, however, the pressure of the modern industrial society has created more and more new problems to forest ecosystems, for instance "The Waldsterben". In terms of growth and yield abnormal stocking levels and changes of growth patterns can be observed. This situation has caused doubt to the use of the old yield tables and has

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made it necessary to find new ways get information about growth and yield.

With modern yield models it is possible to simulate different growing conditions, however, these models require precise estimates of growth and often very detailed information about the stand. The necessary data can often be sampled only at high costs. Generally one can say, that a growth model's resolution increases with the effort used when gathering the data.

The use of aerial photos in forest management has been practiced for several years. But measuring height and other tree parameters on stereo photos was mainly limited by the quality of the aerial photos and by the photogrammetric instruments available. Today the great progress in the field of micro electronics has made photogrammetric instruments and powerful computers available to forest planning. The quality of aerial photos has increased tremendously.

Akca (1984) observed good correlations between photogrammetric crown parameters and the growth of single trees on an experimental plot. The purpose of this study is to evaluate the use of tree parameters taken from aerial photographs. This enables samples that can be used for predicting growth of large areas to be gathered at a low cost.

DATA

The test area, "Hils", is 6000 ha and is located near Einbeck in the State of Lower Saxony in Germany. The main tree species in the Hils are Norway spruce and beech. This study is limited only to spruce.

A grid of sample plots was established over the area and all trees on these sample plots were measured on color infrared area photos (scale 1:5000) with a stereo plotter (Zeiss Planicart E2). For each tree the coordinates of the tree's tip and the lower crown in four directions were taken. For each plot several visible ground points were measured. The ground height, z_j, for the j-tree was determined by a regression model ($z_j=a+bx_j+cy_j$) using the horizontal coordinates x_j and y_j. On 41 randomly selected plots ground measurements were taken and trees for stem analysis were felled. 97 of those were identified on the aerial photos. The volume growth of the felled trees was determined by a program for stem analysis (Nagel and Athari, 1982). For the following investigation only the change in volume in the last five year period will be referred to. The data for the trees from the stem analysis is given in table 1.

Table 1. Data for trees from stem analysis

	Mean	Std Dev	Minimum	Maximum	N
DBH cm	29.48	8.46	15.29	56.36	97
Height m	24.12	5.84	13.29	37.36	97
Age	70.09	21.08	32	115	97

GROWTH PARAMETERS

The growth of a single tree is determined by various parameters which can be classified into the following groups:

- species
- site
- tree size
- crown dimension
- competition

In this study only pure stands of Norway Spruce are evaluated. From the aerial photos and the ground measurements only those parameters are taken into account which can be sampled on an operational basis by forest inventories.

The site is characterized as a function of height and age. The variable age was considered because it is normally known from old stand records in Germany. The tree's size is given by DBH and height from ground inventory. Only height is available from the aerial photos.

For crown dimension several crown parameters were derived from the five coordinates taken in the stereo model of the aerial photos. These are: the length, the surface area, the volume etc.. From ground sampling, crown length and crown width at the base were measured. The crown base was defined as the lowest whirl with three branches having green needles.

The competition of the tree is not specified at this point of the study, partially due to the assumption that the dimension of the crown is also an expression of the past competition.

REPEATED MEASUREMENTS OF AERIAL PARAMETERS

For predicting growth and changes of tree dimensions one is interested in knowing how precisely aerial photo measurements can be repeated. The quality of the aerial photos, the scale, the instrument, and the operator are the main factors. During the study, 245 trees were measured a second time with a lag of two months by the same operator, who did not know that the trees were scheduled for remeasurement. The absolute difference of both measurements are given in table 2.

The mean difference is about 5% for height and crown length. These numbers are comparable with repeated ground measurements, which are taken in stand inventories in Germany. The measurement of the crown length can be repeated with a mean difference of 7.6%. For all parameters very high maximum differences were observed, but only in less than 5% of the data.

Table 2. Absolute mean difference of trees measured twice on the aerial photos

	mean absolute difference	% to mean of parameter	maximum abs. difference
height (m)	1.16	4.9	5.55
crown width (m)	0.18	4.7	1.72
crown length (m)	0.38	7.6	1.42

RELATION BETWEEN AERIAL AND GROUND PARAMETER

The relationship between the photogrammetric measured height and the height measured on the ground is linear (Fig.1). The r^2 is 0.93 and the standard error of the regression coefficient 0.0249. The differences between both parameters decreases with height. The standard error is 1.58m.

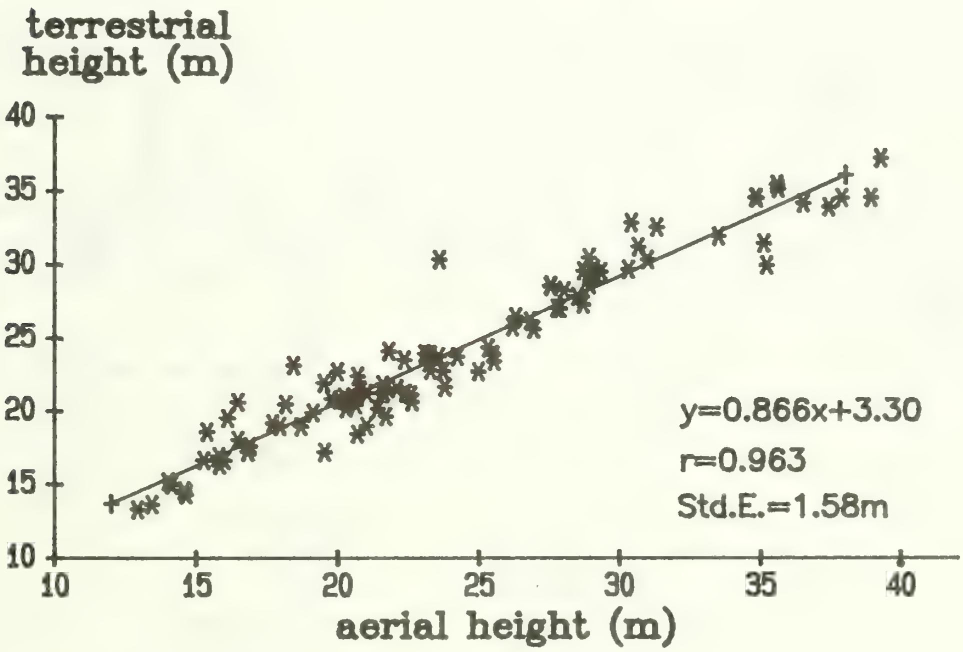

Figure 1. Relationship between aerial and ground height measurement

The relationship between the crown width measured in the stereo model and from the ground is also linear, but is not as strongly correlated as

the height. The r^2 is 0.49. The relationship for crown length is also linear and the r^2 is 0.42.

The observed low r^2 values for the aerial and the ground crown parameter relationships occur because the visible crown in the aerial photo model is much smaller than the crown measured from the ground. Only the lighted part of the crown can be seen in the photos. If trees are standing closely together, the visible part of the tree crown is smaller.

ESTIMATING GROWTH OF SINGLE TREE

The 5-year volume growth (period 1978-1982) was analyzed by multiple regression. Two models were compared, one used photogrammetric parameters and the other used terrestrial parameters. The parameters of the regression models were selected in a stepwise procedure. The final models for the estimation of volume growth using aerial and ground parameters were chosen by the distributions of the residuals. With the computed terms "height over age" and "crown surface area over age", the distributions of the residuals showed a better fit of the regression models to the data.

In the regression equation using the photogrammetric parameters, volume increment is expressed by the crown surface area (CSa), the height (Ha), and the age (Tab.3). The multiple regression coefficient r is 0.83, and the standard error is $0.046m^3$, which is about 41% of the mean volume increment.

The regression equation using the terrestrial parameters contains the variables DBH, height (Ht), crown surface area (CSt), and age. The multiple regression coefficient r is 0.88, and the standard error is $0.039m^3$, or 34% of the mean volume increment.

Table 3. Comparison of statistic values from regression models for estimating growth by aerial and terrestrial parameters

regression model	aerial	terrestrial
Parameters in equation	CSa/age Ha/age Ha^2/age	CSt^3/age Ht/age DBH^2 Ht
multiple r	0.83	0.88
Standard error	0.0456	0.0386
F-Value	81.2	101.7
max. residual	0.139	0.124

The comparison of the statistic values (Tab.3) indicates that the estimate using the ground parameters is better than the estimate using aerial parameters. The standard error of the estimate of the volume

increment is 34% resp. 41% of the mean volume increment and thus within the range known from other growth research.

VALIDATION

20 trees of a small research plot within the test area had been analyzed independently (Kramer et al., 1985). For these trees all the necessary aerial and terrestrial data were available.

The difference between the estimated volume increment of 20 trees using the regression models with the aerial and ground parameters is displayed in figure 2. The predictions of the ground model have higher difference from the actual value than those of the aerial model. The greatest difference is $0.038m^3$. The mean difference is $-0.0014m^3$ for the aerial and $-0.0024m^3$ for the ground model.

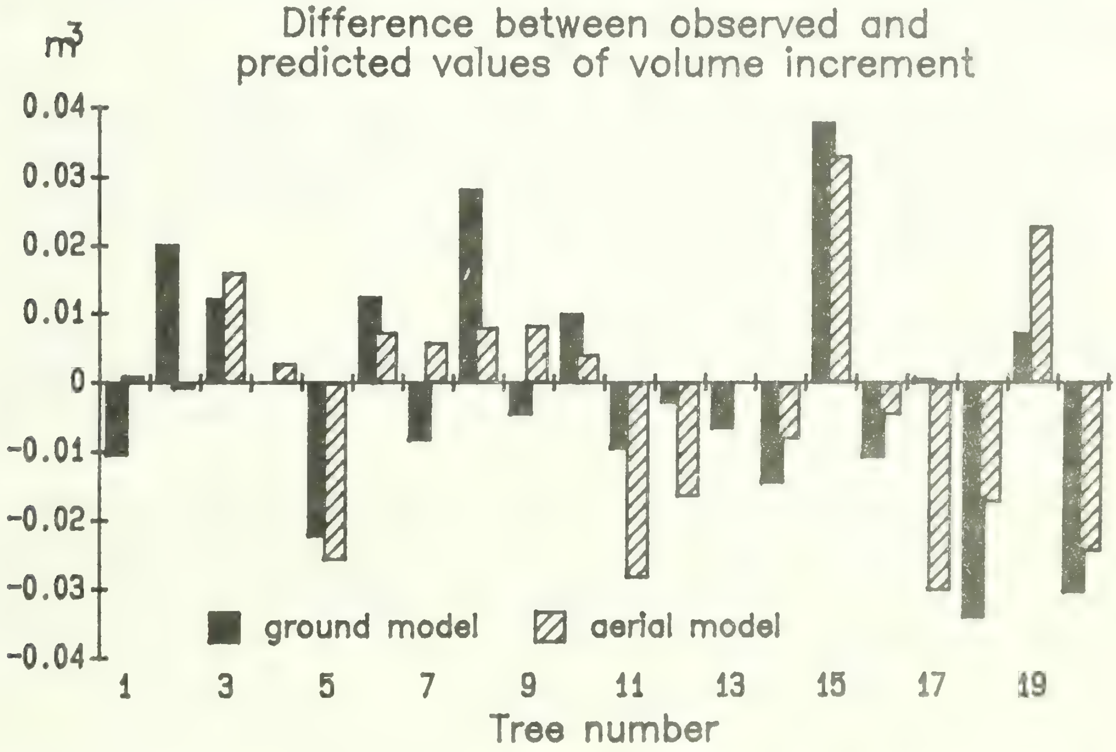

Figure 2. Comparison of the volume increment of 20 trees and the estimates of the regression models

The plot had a total volume increment of 22.2 m^3/ha for the period 1978-1982. Using the aerial and the terrestrial regression equations the volume increment for the plot was 21.2 m^3/ha (95%) and 21.6 m^3/ha (97%) respectively. The plot volume increment estimates calculated by both models are very similar and only about 5% lower than the actual value.

DISCUSSION

The comparison of the data of 245 twice measured trees indicates that tree height, crown width, and crown length can be measured on the aerial photos with equal precision as through ground inventories. High differences could only be observed for very few trees . There is a linear relationship between the photogrammetric crown parameters and the terrestrial ones. The aerial crown measurements are smaller because only the lightened part of the tree crown is visible in the stereo model. This part of the crown is more important for the growth and can the characterized as the "light crown".

The study shows that the estimate of volume growth by ground parameters is little better than from the aerial photo parameters. The standard error from the ground parameters is about 18% less than that of the aerial parameters. One must consider, however, that height and crown length are not usually measured for every tree in ground inventories, so that the error in the growth estimate is approximately equal for both methods under operational conditions.

The standard error for estimating the growth of a single tree seems to be very high with about 41% and 34%, respectively. For the estimate of stand volume growth it will be much smaller, depending on the number of trees sampled. In the validation example on a small research plot, the estimates using the aerial and the ground parameter models are very similar and only 5% below the actual value.

The effort for the ground measurements is about 50 times greater than that of the aerial photo measurements. Because aerial photos also have important value for stand mapping and documentation (Spellmann, 1984), their use for the estimation of volume increment in forest planning should be given more attention.

At this phase of the study, only static parameters have been evaluated. In the future, an improvement in the estimation of volume growth through the use of dynamic variables, such as the change in height and crown dimensions is planned. The necessary data can be sampled by repeated aerial measurements of single trees.

CONCLUSIONS

The quality of aerial tree parameter measurements is comparable to that of ground inventories. The standard error for the estimation of volume increment of single trees by regression analysis is smaller using terrestrial parameters than using aerial ones. It is high, however, for both 34% and 41% respectively. For a research plot, used for validation, both regression models gave similar results and values only 5% below the actual value.

Because aerial photos have important value for stand mapping and documentation, their use in estimating stand volume increment should be

given more attention. In this example the effort required for the tree measurements in the aerial photos and on the ground was 1 to 50.

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A NEW COMPETITION INDEX BASED ON WEIGHTED AND CONSTRAINED AREA POTENTIALLY AVAILABLE

Warren L. Nance, James E. Grissom, and W. R. Smith[1]

ABSTRACT. A new competition index based on modifications to existing Area Potentially Available (APA) methods is proposed. The new method differs from previous APA methods in that it limits or constrains the size of the polygons that can be constructed. Empirical evidence is given for improved growth predictions using the new index.

INTRODUCTION

Due to the pervasive effect of competition on individual tree growth, forest growth modelers continually search for quantitative methods to account for growth effects related to competitive interactions between trees in forest stands. Several studies have compared various competition indices or measures that have been proposed in the literature (Daniels 1981, Daniels et al. 1986). Although the results of these comparisons are not conclusive, the indices based on the construction of Voronoi polygons (see Rogers 1964 for a concise mathematical description) generally compare favorably against other available methods. The methods proposed by Brown (1965), Jack (1967), Moore et al. (1973), and Pelz (1978) are of this type, which are also referred to as Area Potentially Available (APA) methods after Brown (1965).

In two related studies, Nance et al. (1983) and Land and Nance (1987) applied APA-type measures to assess genetic effects on individual tree growth in loblolly pine (*Pinus taeda* L.). In the course of their investigations, these workers developed and implemented (in a FORTRAN program) a new APA-type index that incorporates the idea (suggested in Smith 1987) of limiting the size of Voronoi polygons by constraining the radial influence of individual trees.

In this paper the new competition index is described and its efficacy as a predictor of individual-tree basal area growth is evaluated using data from two loblolly pine field experiments.

CURRENT APA METHODOLOGY

Mathematically, APA indices are based on Voronoi tessellations of points in a plane (Rogers 1964). The points are the cartesian coordinates of the centers of the tree boles at groundline on the forest floor, which is considered to be a plane. The tessellation refers to the

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decomposition of the forest floor into mutually exclusive "tiles" (irregular, convex, nonoverlapping polygons). The polygons are uniquely constructed in such a way that each polygon circumscribes one and only one tree, and <u>the portion of the forest floor within a tree's polygon is nearer in terms of some defined metric to that tree than to any other</u>. If the metric is defined as simple Euclidian distance, then only the distance between trees (not their size) affects the tessellation, and the procedure is referred to as an "unweighted" Voronoi tessellation. If the metric is a function of both tree size and distance, then it is a "weighted" Voronoi tessellation.

Computationally, the construction of Voronoi polygons is quite complex (Green and Sibson 1977, Lee 1980). Basically, the computations consist of two tasks: (1) the location of a set of nearest neighbors for each tree, and (2) the construction of the edges or sides of each polygon. In establishing the location of each edge, lines connecting the subject tree with each of its nearest neighbors are established, and perpendicular lines are then formed to cut these connecting lines. The intersecting perpendiculars form the sides of the polygon. In the case of unweighted tessellations, the perpendicular lines are placed exactly half way between the subject tree and its competitor--thus bisecting the connecting line. For weighted tessellations, the perpendicular bisectors are displaced away from the larger tree and closer to the smaller tree by an amount proportional to their size difference.

The effect of weighting on the placement of the perpendiculars can be expressed in the general form:

$$L_p = WF \cdot L_c \tag{1}$$

where: L_p = distance from the subject tree to the perpendicular line forming an edge between the subject tree and a competitor,
L_c = distance from the subject tree to a competitor, and
WF = a general weighting function defined on the open interval (0,1).

Biologically, it seems reasonable to assume that the area of a tree's polygon represents the space (and resources) available to the tree for future growth, and Brown (1965) introduced the term APA in this context and used unweighted Voronoi tessellations to compute APA. Later, Moore et al. (1973) suggested that weighted Voronoi tessellations be used to compute APA and suggested the following weighting function:

$$WF = D_s^2/(D_s^2 + D_c^2) \tag{2}$$

where: D_s = d.b.h. of the subject tree, and
D_c = d.b.h. of a competitor

Figure 1a shows the unweighted tessellation associated with a small 25-tree plot originally established with 9 interior trees enclosed by a single row of exterior border trees. Five trees had died in the plot. Figure 1b shows the weighted tessellation using the weighting function in equation 2 for the same plot.

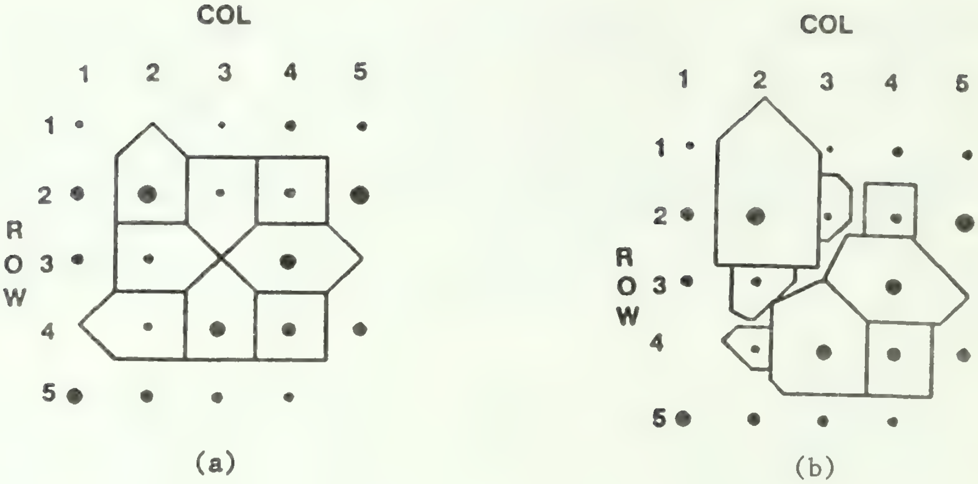

Figure 1. Unweighted (a) and weighted (b) tree polygons for a planted, 5- by 5-tree plot. Circles are proportional in size to tree boles.

Empirically, the area of polygons constructed in this way (especially the weighted polygons) commonly produce simple linear correlations with the future basal area growth of individual trees as high as 0.8, or even higher, under a variety of forest stand conditions (Moore et al. 1973, Nance et al. 1983, Land and Nance 1987, Daniels 1981, and Daniels et al. 1986).

Unfortunately, the correlations can also range as low as 0.3, or even lower, for other stands. Close inspection of the polygons generated in such stands often shows that a substantial proportion of the polygons are inordinately large. As a result, the area of these polygons is so large that the tree's growth cannot match the corresponding expected growth based on the area judged available by the index.

The problem is generally associated with irregular spacing patterns that are created either when the stand is established or through subsequent mortality, or both. For example, the death of only five trees in the plot shown in figure 1a (a 25-percent mortality rate) created a hole near the middle of the plot. The polygons of the larger trees around this hole (trees 2-2, 3-4, and 4-3, where the first number is the row position and the second is the column position) are quite large as a result of expansion into this area. The polygon for tree 2-2 also expanded into the area vacated by the death of tree 1-2, creating a very large, asymmetric polygon.

Attempts to correct this problem through changes in the weighting function are largely futile. If one places less emphasis on relative size (using diameter instead of basal area in the weighting function, for example), the inordinately large polygons causing concern are indeed somewhat constrained. However, the new weight also places less emphasis on size throughout the rest of the stand, and the net result is unpredictable.

A NEW CLASS OF APA INDICES

A general solution to the problem is proposed that involves the addition of a constraining function to equation 1 as follows:

$$L_p = \mathrm{Min}(WF \cdot L_c, CF) \qquad (3)$$

where: Min = minimum function,
CF = a general constraining function, and
L_p, WF, and L_c are defined as in equation 2.

The constraining function serves to limit the maximum expansion of a tree's polygon in any one direction and is only operative when the normal weighted distance $WF \cdot L_c$ exceeds the maximum allowable distance defined by the constraining function CF. For example, if CF is set to a large positive constant (say 10^3) that is never exceeded by $WF \cdot L_c$, then equation 3 reduces to equation 1 (i.e., the polygons are weighted but unconstrained), which is the class of weighted APA indices. If WF is also set to 1/2, then the unweighted APA index results (i.e., the polygons are unweighted and unconstrained). Hence, the class of APA indices specified by equation 3 contains, as special cases, all other existing APA indices.

Of course, interest here centers on the new class of constrained APA indices generated by defining CF to be some real-valued function that is not always greater than $WF \cdot L_c$. Although the constraining function can take any form, biologically motivated functions are recommended. For example, a constraining function that has been found particularly useful is based on the assumption that the distance L_p in equation 3 should be constrained such that L_p never exceeds some function of the expected crown radius of an open-grown tree of the same species and diameter as the subject tree. This can be achieved by setting

$$CF = (\overline{CR}/CRMAX)\ (B_0 + B_1 D_s) \qquad (4)$$

where: $\overline{CR}$ = mean crown ratio of all trees in the stand,
CRMAX = maximum attainable mean crown ratio for stands of the same species,
D_s = d.b.h. of the subject tree (in inches), and
B_0, B_1 = species-dependent coefficients such that
$(B_0 + B_1 D_s)$ = expected crown radius of an open-grown tree of the same species with d.b.h equal to D_s.

The first part of this function ($\overline{CR}$/CRMAX) is a modifier that expresses the cumulative effects of density and age in a developing stand. An approximate value of 0.85 for CRMAX for loblolly pine (based on informal field observations) appears to be a reasonable choice. The modifier is near unity for stands that are very young or have developed under very low densities and decreases toward zero for older stands that have developed under heavy density pressure. The second part of the function, $(B_0 + B_1 D_s)$, generates the expected crown radius of an open-grown tree of the same species with the same d.b.h. as the subject tree. Hence the two parts of the function interact to determine an appropriate constraining function for a particular stand.

For loblolly pine plantations where crown ratio measurements are available, the following specific form of this equation is recommended:

$$CF = (\overline{CR}/0.85)\ (2.0 + 0.80D_s) \tag{5}$$

For unthinned (or perhaps lightly thinned) plantations where crown ratio measurements are not available, a predicted mean crown ratio value can be used, such as the one developed by Feduccia et al. (1979). This substitution results in the following constraining function:

$$CF = (\overline{PCR}/0.85)\ (2.0 + 0.80D_s) \tag{6}$$

where $\overline{PCR}$ = predicted mean crown ratio
$= 248.63 - 35.872 \log(H_D) - 43.565 \log(A_P) - 33.424 \log(T_S)$

and H_D = mean height of dominant and codominant trees in the stand (in feet),

A_P = age of stand (in years), and

T_S = number of trees per acre surviving at age A_P.

Computationally, the introduction of a constraining equation into the general framework of weighted Voronoi tessellations is quite complex, and therefore a complex computer program is required to accomplish the tesselation. A FORTRAN 77 program was written (available on request) that calls user-defined routines for the weighting and constraining functions and is thus capable of constructing the tessellation for any member of the class defined by equation 3. The program not only guarantees that the distance L_p never exceeds CF, but also that the distance to any corner of the polygon is constrained as well. This is accomplished by the insertion of short line segments to approximate an arc of radius CF where necessary to constrain the polygon to that size in any direction. This approach also allows the construction of polygons for border trees, which is not possible for unconstrained APA indices.

Figure 2 shows the formation of weighted and constrained polygons for the sample plot of figure 1, with the weighting and constraining functions specified in equations 2 and 6, respectively. Note that the polygons for trees 2-2, 3-4, and 4-3 are now much smaller than in figure 1b due to the action of the constraining equation, whereas the polygons for the remaining interior trees are essentially unchanged. The gap created by the prior death of tree 3-3 is now much more evident than in figure 1. In addition, polygons have been constructed for the border trees, and, of course, the size and shape of these polygons is strongly affected by the constraining equation.

AN EMPIRICAL EVALUATION OF THE NEW INDEX

PROCEDURES.--Data from two loblolly pine field studies were used to empirically evaluate the new index. The first study, which will be referred to as the "Nelders" study, has been previously reported on by Nance et al. (1983) and by Land and Nance (1987). The second study, referred to as the "Provenance" study, has been previously reported on

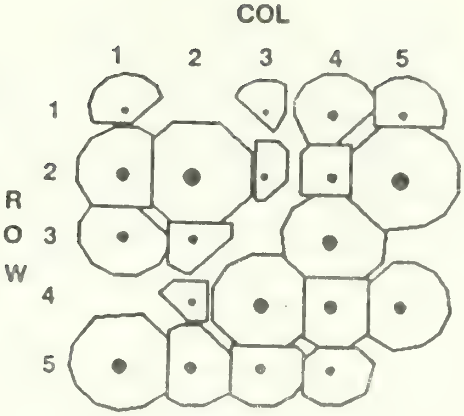

Figure 2. Weighted and constrained tree polygons for planted, isolated 5- by 5-tree plot. Circles are proportional in size to tree boles.

by Wells and Wakeley (1966). The data from these studies is briefly described below, and the reader is referred to the above papers for more details.

The Nelders study consists of 10 isolated "Nelders Wheel" (Namkoong 1965) plantings established in 1975 on a site in northeast Mississippi. Each planting was in the shape of a wheel, with 42 spokes. Each spoke was planted with 7 trees at variable distances along each spoke, resulting in 294 planted trees per wheel and a total of 2,940 planted trees in the study. The variable spacings within spokes provide local initial densities per tree ranging from 436 to 1,210 trees per acre. Although the study was not thinned, subsequent mortality created even wider variation in local density. The inner and outer positions are considered border trees. Annual measurements of d.b.h., total height, and height to live crown were taken on each tree from ages 5 through 10.

The Provenance study consisted of a single plantation established in 1951 on a site near Worcester, Maryland. There were 4,356 trees planted at 6-by 6-foot spacings (1,210 trees per acre). Within the planting, there were thirty-six 121-tree plots (11 by 11 trees), but only the interior 49 trees (7-by 7-tree inner portion) were measured. Hence there were originally 1,764 measurement trees in the experiment. Measurements of d.b.h. and total height were taken at ages 10, 15, 20, 25, and 30. The plantation was lightly thinned at age 16.

Two separate data bases were formed by combining the mapped location of each tree in each experiment with the tree's sequential measurements. These mapped data bases were then repeatedly accessed by the FORTRAN 77 program to accomplish the tessellation for a given age with specified weighting and constraining functions. The two types of constraining functions used were: (1) equation 5 for the Nelders and 6 for Provenance data and (2) CF = 10^3, which nullifies the constraining option. For each constraining function, 20 weighting functions were specified:

$$WF_i(D_s,D_c) = D_s^i/(D_s^i + D_c^i) \ , \ i = 0,0.2,0.4,...,4.0 \qquad (7)$$

For each tree in each tessellation, the program outputs the coordinates of the polygon containing the tree as well as the polygon's area. The polygons were then plotted as a visual verification of the tessellation. The area of each polygon (for nonborder trees) was then used as an independent variable--either alone or in combination with other measured or derived variables--to predict the future basal area growth over time for these individual trees.

RESULTS AND DISCUSSION.--Constraining produces marked improvements in the performance of the index as a basal area growth predictor, especially combined with weighting. For example, table 1 contains the squared correlation coefficients between APA and basal area growth for both types of constraining functions combined with two weighting schemes, WF_0 and WF_2. Overall, the constraining function clearly improves correlations with future growth for both the weighted and unweighted case in both data sets.

TABLE 1. Squared correlation coefficients between APA and basal area growth, with growth based on a 2-year increment from the base age for the Nelders data and a 5-year increment for the Provenance data.

Data set	Weighting	N	Unconstrained			Constrained		
			Age 6	Age 7	Age 8	Age 6	Age 7	Age 8
Nelders	Unweighted	2344	0.16	0.23	0.26	0.58	0.54	0.46
	Weighted	2344	.35	.39	.37	.61	.60	.59
			Age 10	Age 15	Age 20	Age 10	Age 15	Age 20
Provenance	Unweighted	1411	.12	.18	.29	.31	.40	.46
	Weighted	1411	.52	.42	.40	.61	.58	.46

Another desirable feature of weighted and constrained APA is that the procedure appears to be much more robust over a wide range of diameter weights than unconstrained APA, as long as weights invoking i greater than 1 are used (figure 3). The same trend shown for the ages used in figure 3 holds for all other ages. Given this robustness, an i value of 2 appears to be a good choice for weighting.

A third desirable feature exhibited by weighted and constrained APA is that it not only is a strong predictor of basal area growth by itself, but it appears to outperform other individual tree traits used singly or in combination (table 2). Results shown in table 2 hold for other ages in both data sets as well.

These results are encouraging enough to warrant further evaluation with a wider array of mapped stand data for different stand ages, species composition, and genetic structure. In the meantime, plans are underway to use this new class of weighted and constrained APA indices as the nucleus of an individual tree growth and yield prediction system for loblolly pine plantations.

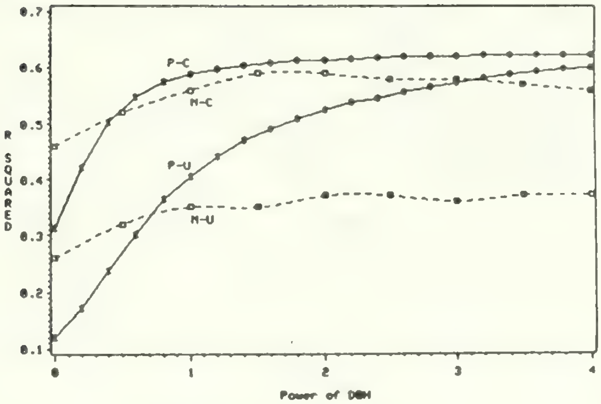

Figure 3. Squared correlation coefficients between APA and basal area growth for two data sets as a function of weighting (power of d.b.h.) and constraining. P - Provenance data at age 10, N - Nelders data at age 8, C - constrained APA, and U - unconstrained APA.

TABLE 2. Squared correlation coefficients for linear models to predict 2-year basal area growth for Nelders data set at 7 years of age.

Individual Tree Measures Included in the Model					Squared Corr. Coeff.
Basal Area	Total Height	Crown Ratio	APA	N	R^2
yes	yes	no	no	2344	.34
yes	yes	yes	no	2344	.45
yes	yes	yes	yes	2344	.62
no	no	no	yes	2344	.60

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A NONPARAMETRIC SURVIVAL MODEL FOR BALSAM FIR AND RED SPRUCE DURING A SPRUCE BUDWORM EPIDEMIC IN MAINE

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ABSTRACT. Individual-tree, spruce budworm caused and blowdown caused hazard functions for balsam fir (Abies balsamea (L.) Mill.) and red spruce (Picea rubens Sarg.) were estimated using the Cox proportional hazards (PH) model. This distribution-free model can generally be described as the incorporation of regression-like arguments into life-table analysis. The Cox PH model is given as: $\tilde{o}(t;Z)=\tilde{o}_0(t)\exp(Z\beta)$, where $\tilde{o}(t;Z)$=probability of dying at time t, given alive before t, $\tilde{o}_0(t)$=baseline hazard at time t, Z=covariate matrix, and β=vector of regression coefficients. $\tilde{o}_0(t)$ explicitly estimates the baseline force of mortality during the epidemic. The model assumes nothing about the shape of the dependent variable's distribution. Of the eight models fit only one was considered monotonic, this indicates that parametric models that are constrained as such are inappropriate. The use of the Cox PH model resulted in greater refinement of mortality trends than the more traditional stand-level analysis. The models fit provide annual estimates of individual tree mortality by cause of death throughout the epidemic.

INTRODUCTION

The prediction of individual tree and stand mortality continues to be an elusive target. Not only do we have to contend with regular mortality (e.g. natural suppression) but irregular mortality (fire, insects, disease, wind, etc.) as well. This paper presents a modelling approach that specifically addresses two types of irregular mortality (spruce budworm-caused and blowdown-caused) for balsam fir (Abies balsamea (L.) Mill) and red spruce (Picea rubens Sarg.) during the latest budworm outbreak in Maine.

The spruce budworm (Choristoneura fumiferana (Clem.)) is a forest insect that periodically causes widespread defoliation of host trees over large areas of eastern North America. Increased population levels of spruce budworm are generally associated with large areas of mature balsam fir and spruce (Picea spp.).

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Previous budworm studies have correlated budworm-caused mortality with a variety of stand density measures. The modelling efforts have generally been at the stand level and have usually found balsam fir and spruce mortality to be positively correlated to host species ba/a and negatively correlated to non-host species ba/a (Batzer 1969; Batzer and Hastings 1981; MacLean 1980). Models of this nature mask any within plot variation that may also account for variation in survival rates. Past budworm mortality models project stand losses over an epidemic, but not during the epidemic. The model to be presented provides estimates of individual tree survival during the epidemic, not just at the culmination.

METHODS

Data used for this study were derived from the Maine Spruce Budworm Growth Impact Study[2]. Plots were remeasured annually from 1975 to 1985 to document the effect of the spruce budworm on the growth and mortality of forests in Maine. Measurements were on 1/20 acre plots for all trees greater than 4.5 inches at dbh. The following records were maintained for each tree: dbh (to the nearest 0.1 inch), crown position (suppressed, intermediate, codominant, dominant), tree status (cull, merchantable, dead), cause of death (budworm, blowdown, harvest, logging damage, other, unknown), total height (nearest 1 ft.), crown length (nearest 1 foot), defoliation of current-year foliage (using classes of (1) none, (2) trace (1-5%), (3) light (6-20%), (4) moderate (21-50%), (5) heavy (>50%)), defoliation of old foliage where the classification is the same as for current-year foliage. From 1975-81 the height, crown length and defoliation measurements where from a 1/50 acre subplot. From 1982-85 all trees on the 1/20 acre plot were measured for the attributes previously measured only on the subplot.

The data were subsequently classified by climatic division within Maine (Lautzenheiser, 1972). The decision to differentiate by climatic division resulted from an anticipated difference in mortality functions between climatic divisions. This resulted in 73 plots (357 balsam fir and 230 red spruce trees) in the Southern Interior Climatic Division (SICD) and 209 plots (1502 balsam fir and 1164 red spruce trees) in the Northern Climatic Division (NCD) being available for model fitting.

MODEL FORM

In survival analysis the rate of change of a survival function is commonly called a hazard function, and is defined as the probability of dying at time t, given alive before t. In mathematical terms this is expressed as: $\tilde{o}(t)=Pr\{\text{death between } t \text{ and } t+1 \mid \text{survival until } t\}$. $\tilde{o}(t)$ is specifically the instantaneous rate of death, thus integration of a function of $\tilde{o}(t)$ over t results in the cumulative survival function. The link between the hazard rate and the cumulative survival function as given by Miller (1981) is: Let $T \geq 0$ have density $f(t)$ and distribution function $F(t)$. The survival function $S(t)$ is,
$S(t) = 1-F(t) = Pr\{T>t\}$,

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[2]Details of MSBGIS objectives and design have been documented by Brann, Reams and Solomon (1983).

and the hazard rate or hazard function $\tilde{o}(t)$ is,
$\tilde{o}(t) = f(t)/1-F(t)$.
The hazard rate has the interpretation,
$\tilde{o}(t)dt = Pr\{t < T < t+dt|T > t\} =$
Pr{expiring in the interval $(t, t+dt)$|surviving past t}.
Integrating $\tilde{o}(t)$,
$\tilde{o}(u)du= \quad (f(u)/1-F(u))\ du = -\log[1-F(u)]|_0^t, = -\log\ [1-F(t)] = -\log S(t)$,
which leads to the expression,
$S(t) = \exp -\int_0^t \tilde{o}(u)du$.

Various parametric and nonparametric models can be used to model the hazard function. If the assumption that the effect of the covariates is to act multiplicatively on the hazard function then this relationship suggests a general model called the proportional hazards model (Cox, 1972).

Parametric regression models such as the exponential, Weibull and logistic can be used to model the proportional hazards function, but restrictions on the form of their hazards make them undesirable for modelling spruce budworm and blowdown mortality during an epidemic. For example, the two parameter Weibull hazard function is given as: $\tilde{o}(t)=\tilde{o}p(\tilde{o}t)^{p-1}$. A specific assumption of the Weibull proportional hazards model (not to be confused with the Weibull p.d.f.) and also the exponential model because it is a special case of the Weibull is that the hazard function is monotone decreasing for $p<1$, increasing for $p>1$, and reduces to the constant exponential hazard if $p=1$. It is unlikely that during a spruce budworm epidemic that any of these assumptions about p apply. When the primary interest is in the effect of regression variables, a variety of approaches may be considered to achieve greater robustness (Kalbfleisch and Prentice, 1980).

An alternative approach suggested by Cox (1972) is to use a more general model that is nonparametric. Cox's PH [1] model can generally be described as the incorporation of regression-like arguments into life-table analysis.

$$\tilde{o}(t;Z)=\tilde{o}_0(t)\exp(Z\beta) \qquad [1]$$

where $\tilde{o}(t;Z)$ is the probability of dying at time t, given alive before t, $\tilde{o}_0(t)$ is the baseline hazard at time t, Z is the covariate matrix, and ß is the vector of regression parameters. The Cox PH model allows $\tilde{o}(t)$ to be arbitrary, that is to increase or decrease at each time t, as opposed to being constrained for the parametric models. The model assumes nothing about the shape of the dependent variable's distribution; it only assumes that the curves for different individuals are parallel. The parametric models traditionally used assume not only parallelism, but also a specific shape for the distribution function. The Cox PH model is classed as a distribution-free model and the estimates of ß depend only on the rank ordering of the dependent variable. As previously alluded to mathematical integration of a function of $\tilde{o}(t)$ over t results in the cumulative survival function,

$$S(t;Z)=S_0(t)^{\exp(ZB)} \qquad [2]$$

where $S(t;Z)$ is the probability of surviving past time t, $S_0(t)$ is the baseline survival estimate at time t, and Z and ß are as defined for [1].

RESULTS

The data were fit to the Cox PH model using the PHGLM procedure of SAS. A significance level of 0.05 was used for variable selection. From a preliminary analysis it was evident that differences by death cause (budworm-caused and blowdown-caused), species (balsam fir and red spruce) and climatic division did exist, and that cause-specific hazard functions by species and climatic division would be necessary. This resulted in fitting eight separate hazard functions [1] and survival functions [2]. Table 1 contains the baseline hazard $\delta_0(t)$ and baseline survival estimate $S_0(t)$ for each time t (t=1,...,9) for each of the eight cause-specific mortality models, and Table 2 contains the parameter estimates of $Z\beta$ for the eight models. Negative regression coefficients correspond to increased survival rates and positive coefficients to decreased survival.

The modelling results of this study indicate differences in survival rates between balsam fir and red spruce trees during a spruce budworm epidemic. These differences by species and death cause are:

(1) Red spruce is much less vulnerable to spruce budworm-caused mortality than is balsam fir.

(2) Red spruce is less likely to blow down than balsam fir, although this difference is much less than for budworm mortality.

Regional differences in mortality rates for each species were also found:

(3) Balsam fir trees in the SICD are more vulnerable to budworm mortality than in the NCD.

(4) The vulnerability of red spruce to budworm mortality is approximately equal in the two climatic divisions.

(5) Both balsam fir and red spruce trees have a greater chance of blowing down in the NCD than in the SICD.

The annual baseline hazards estimated for each of the eight models indicate:

(6) The red spruce blowdown hazard function for the SICD was the only model that exibited a monotone baseline hazard. This indicates that parametric models that constrain the hazard to monotone are inappropriate.

(7) In both the NCD and the SICD the probability of spruce budworm-caused death of balsam fir increased after year 2 and peaked in year 7.

(8) The baseline hazards for the two red spruce-spruce budworm mortality models indicate a delayed response to increased mortality. In the SICD the hazard does not increase appreciably until year 9. The hazard in the NCD increased substantially in year 5 and peaked in years 7 through 9.

Table 1. Baseline hazards ($\tilde{o}_0(t)$) and baseline survival estimates ($S_0(t)$) for each time t (t=1,...,9) for the eight cause-specific mortality models.

	South		North	
t	$S_0(t)$	$\tilde{o}_0(t)$	$S_0(t)$	$\tilde{o}_0(t)$
		Spruce budworm model		
		--Balsam fir--		
1	0.999988	0.00001218	0.921079	0.08290
2	0.999950	0.00003751	0.889377	0.03400
3	0.999751	0.00019620	0.749205	0.17030
4	0.999172	0.00055147	0.489364	0.41847
5	0.998525	0.00061263	0.312791	0.43937
6	0.997598	0.00085847	0.176041	0.56133
7	0.996301	0.00116562	0.059935	1.03072
8	0.995204	0.00100353	0.030252	0.66468
9	0.994046	0.00105495	0.011754	0.90926
		--Red spruce--		
1	1.0	0.0	0.986695	0.013391
2	1.0	0.0	0.960510	0.026885
3	0.999999996	0.0000000038	0.960510	0.026885
4	0.999999992	0.0000000042	0.896583	0.068794
5	0.999999992	0.0000000042	0.859741	0.041930
6	0.999999992	0.0000000042	0.767696	0.113025
7	0.999999983	0.0000000088	0.588605	0.264474
8	0.999999978	0.0000000049	0.450353	0.266539
9	0.999999928	0.0000000491	0.351426	0.247016
		Blowdown model		
		--Balsam fir--		
1	0.838968	0.174915	0.999242	0.000756
2	0.647023	0.258330	0.997682	0.001553
3	0.491466	0.273353	0.997175	0.000507
4	0.430277	0.132581	0.994740	0.002420
5	0.430277	0.132581	0.992435	0.002298
6	0.405197	0.059978	0.989302	0.003122
7	0.405197	0.059978	0.987737	0.001573
8	0.405197	0.059978	0.987517	0.000222
9	0.405197	0.059978	0.983487	0.004022
		--Red spruce--		
1	0.999118	0.000881	0.974210	0.026093
2	0.998636	0.000482	0.952927	0.022063
3	0.998636	0.000482	0.935884	0.018030
4	0.998149	0.000487	0.893752	0.045954
5	0.998149	0.000487	0.872957	0.023513
6	0.998149	0.000487	0.844380	0.033227
7	0.998149	0.000487	0.828245	0.019274
8	0.998149	0.000487	0.820171	0.009791
9	0.998149	0.000487	0.753015	0.085051

Table 2. Parameter estimates of Zß for the eight cause-specific mortality models.

Balsam fir-spruce budworm model (South)

Zß= - 0.43211(S) + 0.07369(SBA) - 0.08611(HBA) + 1.70346(OD) + 3.47622(ND) + 0.00025(FBA)(HBA) - 1.18306(OD)(ND) - 0.01902(OD)(SBA) + 0.01944(OD)(HBA)

Balsam fir-spruce budworm model (North)

Zß= - 0.68882(D)(ND) - 0.41999(I)(ND) - 0.15263(S)(OD) + 0.01693(S)(SBA) + 0.00974(I)(SBA) - 0.88294(OD) + 0.56555(OD)(ND) + 0.01106(OD)(FBA) + 0.02128(OD)(HBA) - 0.02675(FBA) - 0.09027(HBA) + 0.00022(FBA)(HBA) - 0.01163(%FBA) - 0.01568(ND)(FBA) - 0.01123(ND)(SBA) - 0.01911(ND)(HBA) + 0.00018(ND)(FBA)(SBA)

Red spruce-spruce budworm model (South)

Zß= + 0.70833(S)(OD) + 0.00684(OD)(SBA) + 3.52952(OD)

Red spruce-spruce budworm model (North)

Zß= - 1.49138(D) + 0.24098(S)(OD) + 0.01911(FBA) - 1.36954(OD) + 3.49515(OD)(ND) - 10.34842(ND) - 0.03903(ND)(FBA) + 0.00032(ND)(FBA)(SBA)

Balsam fir-blowdown model (South)

Zß= - 0.08379(FBA) + 0.00082(FBA)(SBA) - 1.18573(OD) + 0.10014(%FBA)

Balsam fir-blowdown model (North)

Zß= + 0.72949(D) + 0.84921(OD) - 0.00891(%FBA) + 0.00007(FBA)(SBA) + 0.00024(FBA)(HBA) - 0.36393(OD)(ND) - 0.00689(OD)(HBA) + 0.01954(ND)(HBA)

Red spruce-blowdown model (South)

Zß= + 2.58365(S) + 0.00966(OD)(HBA)

Red spruce-blowdown model (North)

Zß= - 0.30709(I)(OD) + 0.07879(FBA) - 0.08676(SBA) - 0.11241(HBA) - 0.02657(OD)(FBA) + 0.02552(OD)(SBA) + 0.02952(OD)(HBA) - 0.04910(ND)(SBA) + 0.00066(ND)(FBA)(SBA)

where, D=1 if dominant tree, 0 otherwise, I=1 if intermediate tree, 0 otherwise, S=1 if suppressed tree, 0 otherwise, FBA is the initial balsam fir ba/a, SBA is the initial spruce ba/a, HBA is the initial hardwood ba/a, ND=1 if the tree is on a plot that has at least one fir or spruce tree with >50% defoliation of current-year foliage for more than 5 years, 0 otherwise, OD is the nine year average (1976-84) of the average annual cumulative plot defoliation ratings. The average annual cumulative plot defoliation is the average of the annual cumulative defoliation ratings over each spruce and fir tree rated on the plot.

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(9) The baseline hazard for both the red spruce and balsam fir blowdown models in the SICD peaked early in the epidemic. For balsam fir no

blowdown occurs after year 6 and for red spruce no blowdown occurs after year 2.

(10) The baseline hazards for both the red spruce and balsam fir blowdown models in the NCD indicate cyclic trends that coincide with one another. It is thought this may be associated with the windstorms.

The influence of the independent variables on mortality rates for each of the eight models fit can be generalized as follows:

(11) Budworm-caused death of balsam fir in the SICD is generally greatest in stands with high levels of fir and spruce ba/a and low levels of hardwood ba/a. Mortality increases with increasing cumulative plot defoliation. Suppressed trees have the greatest chance of survival.

(12) Budworm-caused death of balsam fir in the NCD is greatest in stands with low levels of hardwood ba/a and is least in stands with high levels of hardwood ba/a. High levels of fir and hardwood ba/a are also associated with increased tree mortality. High levels of spruce ba/a increase mortality rates for suppressed and intermediate crown classes much more than for domianant and codominant trees. Mortality generally increases with increasing cumulative plot defoliation.

(13) Budworm-caused mortality of red spruce in the SICD increases with increasing cumulative plot defoliation and spruce ba/a. Suppressed trees have the greatest chance of dying.

(14) Budworm-caused mortality of red spruce in the NCD is greatest at high levels of spruce and fir ba/a.

(15) Blowdown mortality of balsam fir in the SICD is the only model where all crown classes have equal probabilities of mortality. The probability of blowdown increases as spruce ba/a and the percentage of fir ba/a increase, and decreases with increasing cumulative plot defoliation.

(16) Blowdown mortality of balsam fir in the NCD increases with increasing cumulative plot defoliation. Trees on plots with ND=0 have a greater chance of blowing down than when ND=1. When ND=0, blow down increases with increasing levels of fir and spruce ba/a. When ND=1, the greatest chances of blowdown are associated with high levels of fir, spruce and hardwood ba/a or high levels of just fir and hardwood ba/a. The lowest rates of blowdown are associated with high levels of fir and spruce and low levels of hardwood ba/a. Dominant trees are most likely to blowdown.

(17) Blowdown deaths of red spruce in the SICD increase as cumulative plot defoliation and hardwood ba/a increase. Suppressed trees are most likely to blowdown.

(18) Blowdown deaths of red spruce in the NCD generally increase as cumulative plot defoliation increases. Trees on plots with ND=0 have a greater chance of blowing down than for trees on plots with ND=1. Intermediate trees are least likely to blow down.

CONCLUSION

Only one of the eight models fit exibited a monotone baseline hazard. This indicates that parametric models that constrain the baseline hazard as monotone are inappropriate. The Cox PH model allowed greater refinement in assessing mortality trends than the traditional stand-level analysis. The annual baseline hazards provide explicit estimates of the rate of change of budworm and blowdown mortality throughout the epidemic.

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FUNCTIONS FOR FORECASTING OF TIMBER YIELDS

Ulf Söderberg

ABSTRACT. This paper describes a method of constructing functions for long-term forecasting of timber yields. The functions are based on sample trees from the National Forest Inventory in Sweden. The species included are Scots pine, Norway spruce, birch, beech, oak and other broadleaves. A growth model is used as a basis for constructing the functions.

Individual tree growth is estimated from five-year "normal" basal area increment over bark. Volume and volume increment are estimated by means of form height functions. Special attention has been paid to effects of earlier treatments on growth in the data set and on effect of thinnings on form height, when the form height functions are applied. The functions are based on undamaged trees only, while the damaged trees are used for estimating the effects on growth of different types of damage.

A study on tree mortality, based on unthinned permanent plots has been employed.

A growth simulator was constructed. Comparison was made with yield of permanent plots and yield tables for spruce, birch and beech. The results indicate that the growth simulator estimate growth and yield satisfactorily. Standard deviation between observed and estimated growth is about 10 per cent.

INTRODUCTION

The forecasting of growth and yield has been a substantial part of forest research since the beginning of the 19th century. The methods used have developed with the use of statistical methods and computers. Regression analysis was first used by Petterson (1932) and Näslund (1935) to develop increment functions.

In spite of the fact that there has been much research into forest growth and yield, our knowledge of the capacity for growth and yield of many types of forest and treatment is still limited.

Various methods are used for forecasting timber yields. Two main methods are used: modelling of tree growth and modelling of stand or plot growth. Munro (1974) categorized growth simulators according to the unit of growth used for prediction and according to the spatial arrangement of the individual trees. Tree growth models are divided into distance-dependent and distance-independent models.

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The method used here can be categorized as a distance-independent model. It is based on a method developed by Jonsson (1974, 1980).

The species included are Scots pine, Norway spruce, birch, beech, oak and other broadleaves, and the functions cover the whole of Sweden. These functions are constructed with the aim to be used as a component in two different forest management planning systems in Sweden.

MATERIAL AND METHODS

This study is based on sample trees collected by the Swedish National Forest Inventory (NFI) during the years 1973-1977. The NFI is an annual inventory covering the whole of Sweden, the design of which is systematic cluster sampling, where the cluster is a square with a side length of 1 000-1 600. Along the sides of the square 3-5 plots with a radius of 10 metres were laid out systematically.

The data used here are confined to forest land. Sample trees are selected, with a higher probability for large trees, and no sample trees are taken of diameter less than 5 cm. The sample trees are measured to determine volume and an increment core is taken, which is measured for age and increment at the department of Forest Survey. Damage and its causes are noted for the sample trees.

The material is representative of the population of Swedish forests which is an advantage for this study. A shortcoming of the material is that the plots are temporary, also that knowledge of historic treatments is insufficient. The composition of the data is presented in Table 1.

Table 1. The distribution of the number of sample trees by species and by damaged and undamaged trees

Species	Undamaged	Damaged	Total
Scots pine	10 615	1 014	11 629
Norway spruce	14 721	1 464	16 185
Birch	3 460	394	3 854
Other broadleaves	1 148	190	1 338
Beech	219	6	225
Oak	292	11	303
Total	30 455	3 079	33 534

The data set was first adapted for the final analysis. Some of this work:

- estimation of site index
- determination whether the plots are fertilized or not
- correction for weather conditions (annual ring indices)
- generalization from sample trees

was done within the Hugin-project and briefly presented in Hägglund (1981).

A set of bark functions was developed and used in connection with the reconstruction of trees and plots. Since the growth period of functions is set to five years, growth is reconstructed up to five years before the date of plot measurement. The growth of sample trees is reconstructed by means of the measurements of the increment core, and only calipered trees are reconstructed by generalization from sample trees, whereby the state of the plot can easily be calculated.

A method to test whether the data set contains data resulting from record or measurement error has been developed. Test quantities are established from standard deviations and from the partial correlation coefficients of simple functions which have been derived. At the used limits of test quantities, a greater proportion than could be expected by chance, was revealed by the test. This indicates that record errors exist. The trees outside the limits were eliminated from the data set.

A growth model developed by Jonsson (1969, 1980) is used as a basis for constructing the functions. In the increment function, five-year "normal" basal area growth over bark is used as dependent variable. The increment is expressed as a function of the following factors: basal area and age of the tree, density of the plot (basal area m^2/ha) combined with earlier treatments of the plot, the social rank of the tree on the plot, proportion of different species, site index referring to most suitable species, other site factors such as mineral soil or peatland, soil moisture, surface/surface water flow, forest type (vegetation type), inclination and direction of slope. Geographical location is described by using latitude, altitude and climatic regions. A total specification of the model can be found in Söderberg (1986).

Separate functions have been derived for northern, central and southern Sweden. Within these regions the data set is divided into two age-groups, with the point of division at about 50 years at breast height, and separate functions are derived for the two groups, for most species. Functions have been constructed for the following species: Scots pine, Norway spruce, birch, beech, oak and other broadleaves.

The functions are based on undamaged trees only, while the damaged trees are used for estimating the effects on growth of different types of damage.

The specification of the growth model, concerning density of plot combined with historic treatment of the plot, is based on the character of the data set as well as on the fact that the effect of thinning on the growth of a tree is desribed, Jonsson (1980). The thinning response functions are shown to be dependent on thinning grade and varies with time. The response to thinning varies with site index.

The material is not entirely suitable for estimating the effects of thinning on growth. It is possible, however, to distinguish between the growth of trees not affected by thinning and the growth of trees affected by thinnings.

Volume and volume increment are estimated by means of form height functions. The form height functions are based on the state of the tree at the time of measurement and are therefore static. The model is specified using the same variables as in the growth functions. Special attention has been given to changes in form height due to thinning. The data set used here is not suitable for analysing the effects of thinning on form height. Several reports (Näslund 1942, Petrini 1936, Abetz 1976, Vuokila 1960) show that form (form height) will deteriorate as a result of thinning. For this reason, the form height functions are constructed in such a way that form height deterioration is generated with the help of the variable of plot basal area in connection with thinnings.

A study on tree mortality has also been performed, in which material from permanent research plots has been used. Unthinned plots only have been used. The number of measurements per plot varies between 1-11 and in all, 532 measurements from 82 plots have been used. The oldest plots have been followed for more than 70 years.

From the point of view of silviculture, the data set used refers to an extreme population, since no treatments have been applied. To define the proper application of the mortality function, a function which estimates the "maximum" plot basal area has been derived from the same data set. In a forecast the basal area estimated by this function is compared with the basal area generated by the growth functions, and if the latter is the greater, then the above-mentioned mortality function is used, otherwise other mortality functions are applied.

In the basal area function, basal area (m^2/ha) is estimated by means of total age, site index, number of stems and the proportion of different species. The dependent variable is transformed by the natural logarithm.

The dependent variable of the mortality function is annual mortality, as a proportion of basal area. Mortality is estimated by total age, basal area, site index and proportion of different species.

RESULTS

As a result of specifying the model, 20 basal area increment functions for individual trees were developed. The dependent variable is transformed by the natural logarithm. The residual standard deviations of the functions are between 0.4-0.6 (40-60 %), where the functions for broadleaves generally have the greatest standard deviation, since they include several species. The increment of several trees can, however, be estimated with fairly high accuracy.

The functions are derived from undamaged trees, to exclude the influence of damaged trees on partial relationships and on the increment level of the functions. This means that the increment level of the functions is not affected by damage to trees in the data set. This approach makes it possible to estimate the effects of different types of damage on tree growth, and in addition, a greater flexibility is attained in applying the functions.

The proportion of damaged trees is generally close to 10 % in the treated units of the data set, with the exception of birch and other broadleaves in northern Sweden, where the proportion is about 25 %. On the average, the reduction of increment due to damage is ca 20-25 % for conifers. For broadleaves the reduction is more variable. This variation is probably due to the fact that several species are included in this group and that these species have different growth rates. Fast growing species are shown to have twice as high a proportion of damaged trees as undamaged ones.

The specification of the model of the form height functions has resulted in 12 derived functions. The residual standard deviations about the functions for conifers were 0.11-0.13, for broadleaves 0.14-0.19. Residuals of the functions were examined, and no signs of systematic errors were found.

Special attention has been paid to the effect of thinnings on form height. Plot basal area is used as a variable in the form height functions. The reduction of plot basal area when thinnings are performed, will cause a slight reduction on form height of the trees after thinning.

The form height functions have been tested with other data than those on which they are based. One of these studies has been presented by Lindgren (1984), who studied the use of the form height functions as a method of estimating volume of a compartment, as compared to conventional methods. He stated that the use of form height functions in this way is very efficient. In addition, a comparison has been made with volume functions for small trees (Andersson 1954). This comparison indicated that the form height functions can be used for trees less than 5 cm at breast height, for some purposes. In all, the functions seem to work reasonably well.

COMPARISONS WITH MEASURED GROWTH AND YIELD

A growth simulator was constructed. The fundamental feature of the growth simulator is as follows. From an initial state the basal area increment of the trees on the plot is estimated. This increment is added to the initial basal area of the tree and this together with the new state of the plot constitutes the initial state of the next growth period. Volume is estimated by the form height functions at the start and at the end of the growth period, and volume increment is calculated as the difference in volume at these points in time. Mortality is incorporated for every growth period.

To estimate growth after the plot is thinned, thinning response functions (Jonsson 1980) are used to describe the development of a tree after thinning. The applications of the thinning response functions implies that the increment of a tree in the absence of treatments has to be known. Therefore, the increment functions are applied as though no treatment has been carried out. Thus the growth of a plot after thinning consists of increment generated by the increment functions, added to the thinning response for the trees

left after thinning.

The growth according to the functions is compared with measured growth on permanent plots. In the selection of plots the intention has been to use plots proportionately extreme as compared with the data set used to develop the functions. For most of the plots, not only can the initial state of the plot be regarded as extreme, but also the treatments. The selection of plots also aimed at using as long series of observed developments as possible. The period of observation varied between 19-63 years, and the average period was 45 years.

Table 2 shows the estimated and observed annual basal area for the plots. On the average for all plots, the increment was overestimated by 4.3 %. The standard deviation about the mean was 11.8 %. On four of these plots, however, there were signs of damage to the trees (root rot and pitchy wood). This damage causes a marked reduction of the increment of a tree, as shown earlier. It is therefore natural that the growth of these plots is overestimated by the functions. If the damaged plots are omitted, the mean is underestimated by 0.7 %. The standard deviation is 6.9 %.

Table 2. Observed and calculated annual basal area increment during the observation period on the compared plots. The difference is presented in m^2/ha and in per cent of the observed increment. Permanent plots

		Annual basal area increment (m^2/ha)			
Plot no.	Observed	Calculated	Difference	Diff.,%	Remark
611:2	0.15	0.13	0.02	11.1	
629:2	0.34	0.42	-0.08	-24.3	Pitchy wood
632:2	0.34	0.32	0.02	7.4	
265:3	0.37	0.39	-0.02	-6.6	
3:3	0.42	0.40	0.02	4.2	
608:3	0.43	0.40	0.03	5.0	
740	1.20	1.29	-0.09	-7.0	
22:2	0.26	0.29	-0.03	-11.1	
718	0.84	0.84	-0.00	-0.6	
58:1	0.35	0.35	0.00	0.9	
383:1	0.47	0.58	-0.11	-25.0	Root rot
382	0.38	0.35	0.03	7.8	
278	0.43	0.39	0.04	8.9	
503	0.39	0.44	-0.05	-12.5	Root rot
222	0.60	0.64	-0.04	-7.3	
71	0.41	0.42	-0.01	-1.8	
444:2	0.44	0.55	-0.11	-26.4	Root rot
T4:2	1.17	1.17	-0.01	-0.9	

Plots of Scots pine situated in northern Sweden were also compared. The period of observation was between the years 1963-1982, and the plots were remeasured in the same way as the permanent plots. The remeasurement made it possible to compare three growth periods. The last growth period was not corrected by annual ring indices, since

these were not available for the last years of the period. For the two first growth periods, ring indices were taken into account. In total, the increment according to the functions was 1.8 % higher than the observed increment for the whole period of observation.

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A GROWTH AND YIELD MODEL FOR EUCALYPT PLANTATIONS IN PORTUGAL

Margarida Tomé (1)

ABSTRACT. A distance-independent growth and yield model is being developed based upon measurements of 120 permanent plots (area about 1000 m^2). These plots are annually remeasured, with all trees tagged, and established in Eucalyptus globulus plantations in Central and North Portugal. The number of remeasurements ranges from 3 to 16. Plots cover a wide range of situations, namely: different geographic locations, coastal, inland and coastal-inland; spacings ranging from 2.0X2.0 to 5.0X4.0 m; dominant heights at age 10 between 12 and 28 m; basal area at age 10 between 8 and 32 m^2. Particular emphasis is being put on influence of site factors in both growth functions and relationships between variables (taper curves, height-diameter curves) to make the model flexible enough to be used in different situations.

INTRODUCTION

Eucalyptus ssp., exotic trees originally from Australia, were first introduced in Portugal as ornamental near farmhouses, in roadside plantations or as windbreaks. The first eucalypts to be planted in Europe are thought to be those planted in 1829 at Vila Nova de Gaia near Porto, but reliable records are not available before 1852 (Pimentel, 1876; Fao, 1981). From 1885 large plantations began to be established in several regions of the country, but without any previous research about what species or silvicultural techniques should be applied in each particular environment. After the second World War, expansion of the pulp industry in Portugal lead to an increase of eucalypt plantations, 95% of them being made of E. globulus. With the increasing demand for eucalypt wood by the pulp industry there has been a shift towards an intensive silviculture and improved forest management practices. As a consequence of this fact, forest managers are faced with evaluation of different management alternatives and the need for growth and yield forecasts becomes essential.

Some growth information on E. globulus can be found in Portugal (Tomé, 1983), but most of the published works were based in old plantations (with a high number of trees per ha and poor soil mobilization at planting, conditions somehow different from the present ones), limited to restricted areas and most of them were based in graphical techniques. Pulp industries have played an important role in eucalypt growth studies, establishing permanent plots in their plantations. CELBI's earlier permanent plots date from 1970. Several remeasurements of these permanent plots are now available and, as a

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consequence, a broad research program on growth and yield of eucalypt plantations is being developed at the Department of Forest Engineering (ISA, Lisbon) in colaboration with CELBI. The objective of this project is to develop several growth projection systems for eucalypt plantations, according with specific objectives. Obviously these systems are not mutually exclusive and some of the programs and/or model components are common to different systems. According to the principal problems arisen for eucalypt silviculture, three main objectives have been selected for development of growth projection systems:

- Forecasts of future wood supply for the pulp industry, based on forest inventory data.
- Optimization of forest management techniques and study of alternative ways of managing eucalypt stands for uses other than pulp.
- Study of the impact of insect (Phoracanta semipunctata) infestations on yield of stands.

This paper describes the MOPREU system and presents a preliminary version of the SICREU subsystem for 1st generation stands, designed to meet the first of the above objectives - to project inventory results for forecast of future availability of wood for pulp mill industries. Due to the rapid expansion of the pulp industry which has not been adequately compensated with compatible afforestation rates and/or improvement of existing stands, the annual cut is thought to equal or even exceed the annual growth of our forests. The programming of future activity of the pulp industry is highly dependent on projecting consistently the existing stands, under alternative scenarios of exploitation, which can only be accomplished with a consistent growth model.

STRUCTURE OF THE SYSTEM

The MOPREU system has been conceived in an hierarchical structure with three levels - tree, stand and region - as schematized in figure 1.

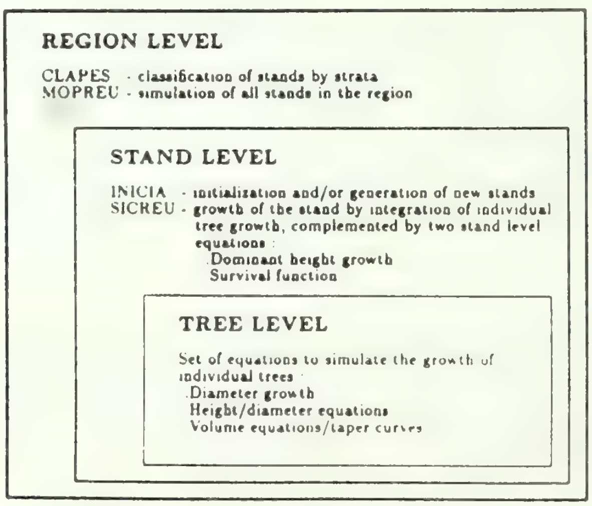

FIGURE 1. Hierarchical structure of the MOPREU system

TREE LEVEL. The tree level consists of a set of growth functions and relationships between variables (allometric or others), which simulate the growth of individual trees:

1. Diameter growth

2. Height-diameter equations

3. Volume equations and/or taper curves

As regeneration of eucalypt stands can be made by seedlings (1st generation) or sprouting (2d, 3d and 4th generations) at least two different sets of these equations are needed on this level. It is also desirable to have different equations according to different site factors as eucalypt seems to be particularly sensitive to environmental variation.

STAND LEVEL. The stand level (figures 2 and 3) consists of two FORTRAN programs:

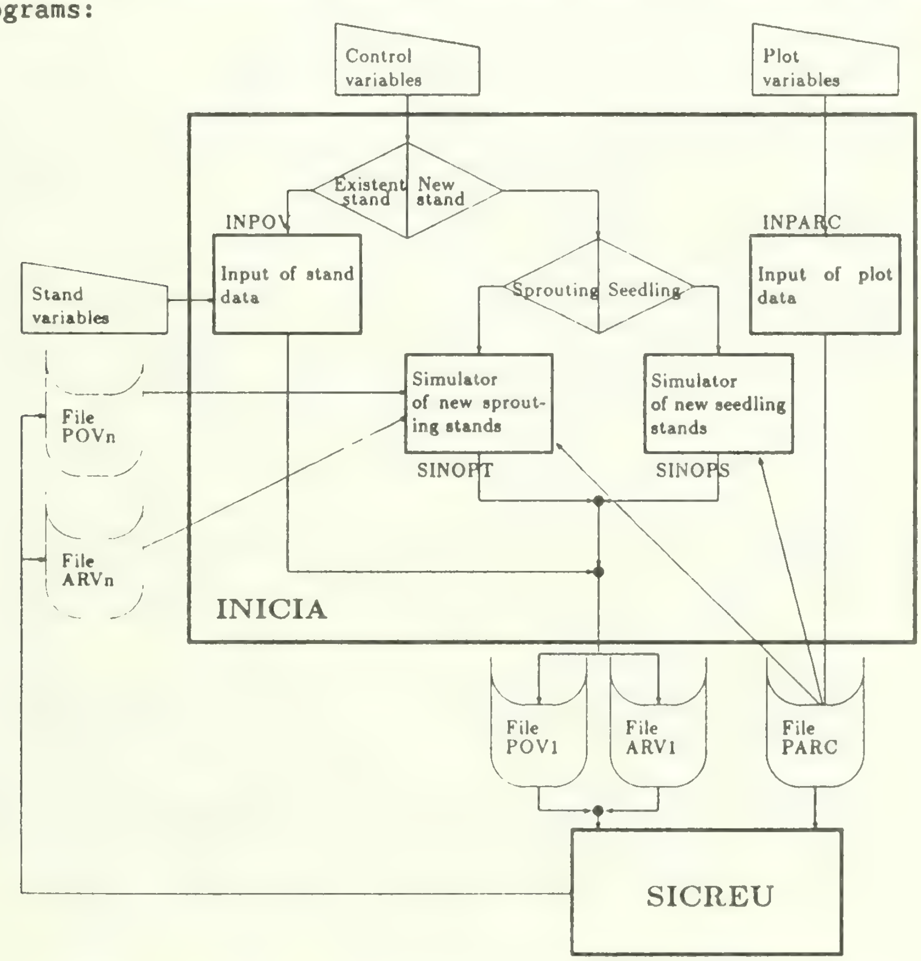

FIGURE 2. INICIA - initialization of tree, stand and plot files

1. INICIA, INICIAlização de ficheiros (initialization of tree, stand and plot files) - input of data and simulation of new stands both for 1st generation - simulation of a new stand based on site

characteristics such as site index and initial number of trees per ha - and 2d, 3d or 4th generations - simulation of a new sprouting stand based on site characteristics, characteristics of previous stand and a stumps mortality rule (figure 2).

2. SICREU, SImulador para o CRescimento do EUcalipto (growth simulator of eucalypt) - simulates the growth of each stand based on tree level equations 1,2,3 ,complemented by stand level equations: dominant height growth (site index equations) and a mortality function (figure 3).

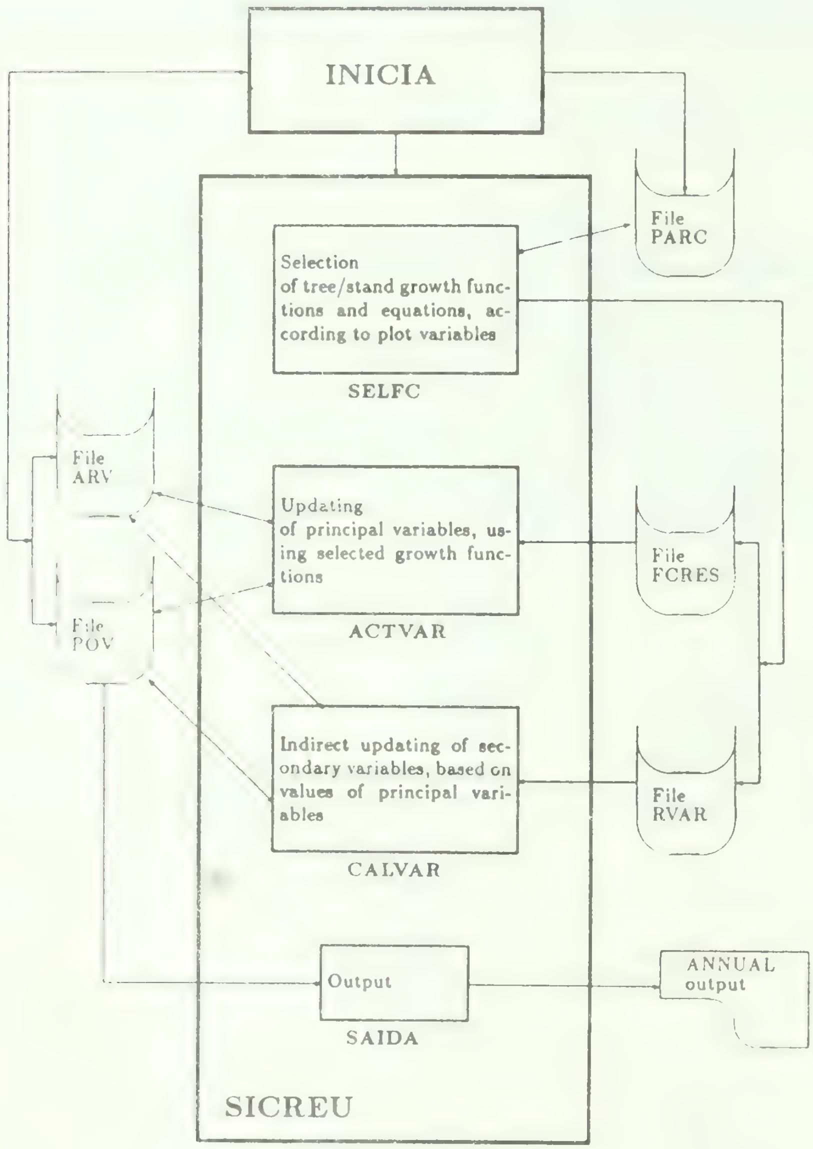

FIGURE 3. SICREU - growth simulator of eucalypt

REGION LEVEL. The region level consists of two FORTRAN programs (figure 4):

1. CLAPES, CLAssificação dos Povoamentos em EStratos (classification of stands in strata)

2. MOPREU, MOdelo de PRodução para o EUcalipto (yield model for eucalypt) - using stand level components INICIA and SICREU and management options (such as spacing, stumpage age, new plantations per year ...) projects all stands in a region.

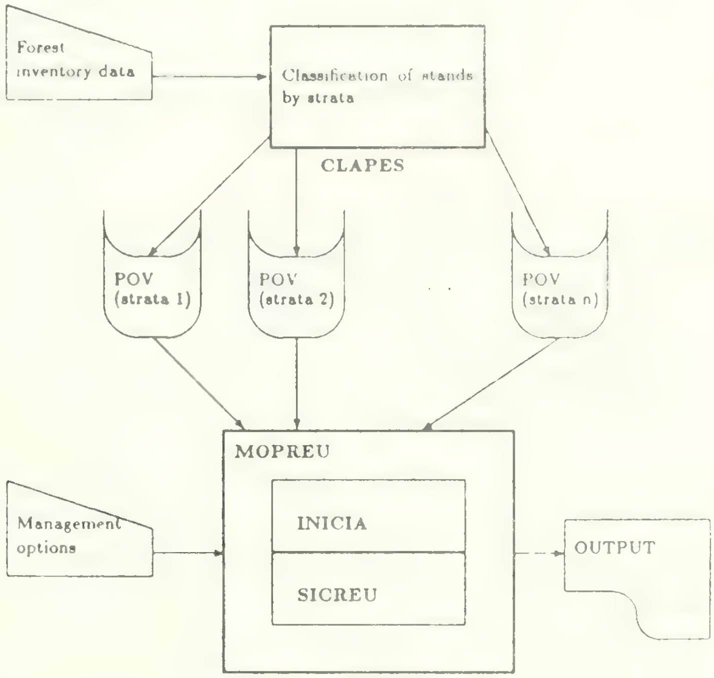

FIGURE 4. MOPREU - yield model for eucalypt (region level)

DATA BASE

Data for this study came from CELBI' s permanent plots, established from 1970. These plots are located throughout most of the eucalypt area of northern-coastal (region 1), central-coastal (regions 2,3) and central-inland (regions 4,5,6) Portugal and have been annually remeasured several times, with some exceptions of longer periods. Most of the plots were established in the 1st generation (84%), some of these being now in the 2d generation (table 1). Table 2 sumarizes number of observations per plot and ages of first and last remeasurement.

BUILDING THE MODEL

The model described above is a very large project whose complete execution has not yet been accomplished. In order to get useful results as soon as possible, we programmed the building of the model in such a way that preliminary results could be used before the conclusion of the project.

TABLE 1. Number of plots (total,still existing) available for the study

Gen.	Region 1		Region 2		Region 3		Region 4		Region 5		Region 6	
1	12	2	51	44	–	–	10	–	4	3	7	5
1–2	6	4	20	12	2	2	–	–	3	2	–	–
2	2	–	7	1	4	1	–	–	6	–	–	–
2–3	–	–	1	1	–	–	–	–	–	–	–	–
3	–	–	1	–	–	–	–	–	–	–	–	–
3–4	–	–	1	1	–	–	–	–	–	–	–	–
4	–	–	–	–	–	–	–	–	–	–	–	–

TABLE 2. Characterization of plots available for the study

Generation	N. of observations min	med	max	Age 1st remeasurement min (years)	med	max	Age last remeasurement min (years)	med	max
				REGION 1					
1	3	6.8	11	2.7	10.1	17.0	11.5	16.1	19.8
2	1	3.2	8	3.6	4.6	7.2	3.6	7.2	15.6
				REGION 2					
1	4	6.7	16	3.8	7.7	15.8	10.7	13.8	24.7
2	1	3.9	10	1.5	5.0	10.0	3.6	8.3	[illegible]
3	4	4.7	5	3.6	7.6	11.1	11.6	12.3	13.8
4	5	5.0	5	3.6	3.6	3.6	11.6	11.6	11.6
				REGION 3					
1	10	10.0	10	4.7	4.7	4.7	14.5	14.5	14.5
2	3	5.3	7	2.6	7.0	9.2	4.5	12.3	17.6
				REGION 4					
1	6	6.6	7	6.2	8.1	9.2	13.2	14.6	16.2
				REGION 5					
1	10	12.0	15	0.8	2.7	6.5	11.2	14.0	16.0
2	1	4.2	6	2.4	7.2	10.2	2.4	10.2	13.8
				REGION 6					
1	2	7.0	9	1.2	2.9	7.0	1.8	11.4	14.6

As all published works on growth of eucalypt in Portugal and most of the data base available refer to 1st generation stands (as well as most of existing stands), the first submodel chosen was a preliminary version of SICREU to be used for 1st generation stands in the northern-coastal region (regions 1,2,3), which is ecologically more suitable for eucalypt and to which belong 78% of the permanent plots available for the study. Site index for these plots (base age 10) ranges from 12 to 28m and spacings from 2.0X2.0 to 4.0X5.0 m.

This model is now available using the following equations:

Surviving:

$$N_{t+1} = 0.9877\ N_t$$

Site index:

$$HD_{t+1} = 1.0842\ HD_t^{(0.9794+1.1365(A_t^{-1}-A_{t+1}^{-1}))}$$

Dbh increment:

$$DBHIN = -1.5402+0.5663\ MAID+4.6188\ INVBAS-12.6520\ MBAS+0.4242\ LOGHD$$

where A_i is age at time i; N_i is number of trees per ha surviving at age A_i; HD_i is dominant height at age A_i; DBHIN is annual increment in dbh at time t; MAID is mean annual increment in dbh at time t; INVBAS is inverse of basal area per ha at time t; MBAS is mean basal area at time t; and LOGHD is logaritm of dominant height at time t.

These equations have been selected among several other candidates based on their statistical qualities, biological behaviour and simplicity. Some of these equations can probably be improved, but were thought to be precise enough for this preliminary version of SICREU, as projections behave well when compared with real growth of validation plots that have been withheld for this purpose (figures 5a,b,c).

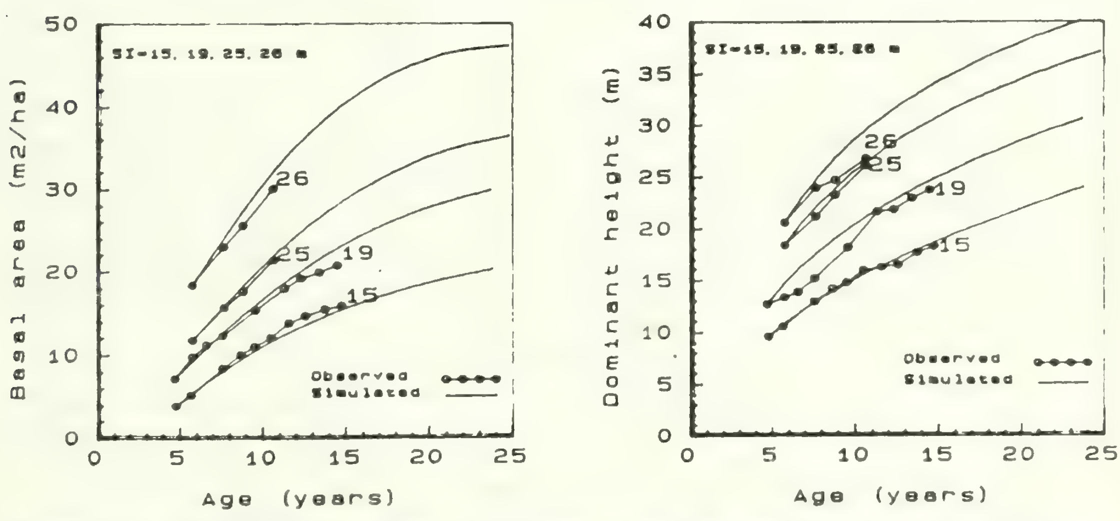

FIGURE 5a. Observed and simulated basal area/ha and dominant height for some of the plots of the validation data set (spacing 3x3 m)

As improved equations are obtained they can be easily incorporated into the model, given the modular structure of the program.

Volumes per ha (total and/or merchantable) can be estimated with volume equations published by Leal (1982).

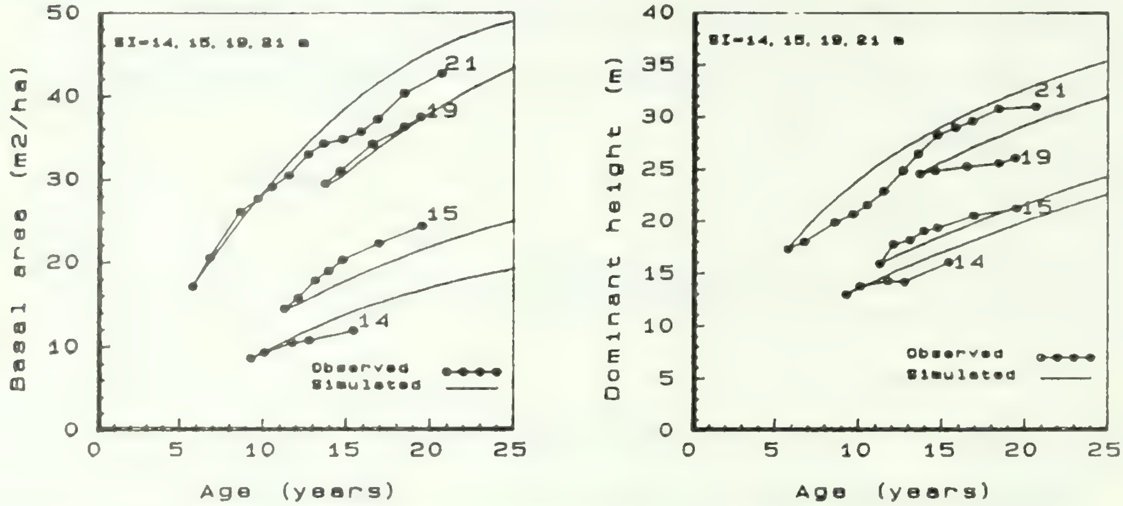

FIGURE 5b. Observed and simulated basal area/ha and dominant height for some of the plots of the validation data set (spacing<3x3 m)

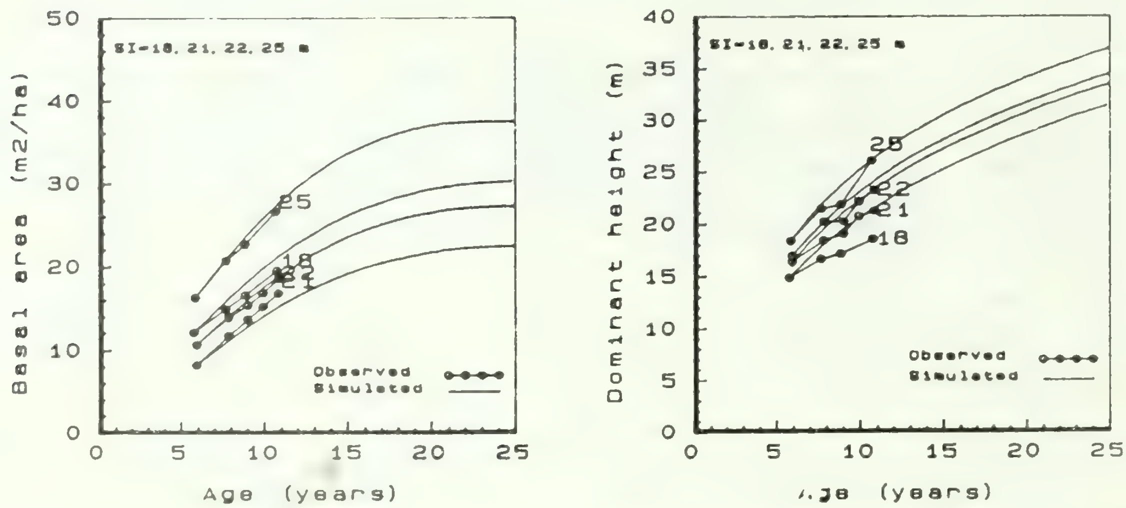

FIGURE 5c. Observed and simulated basal area/ha and dominant height for some of the plots of the validation data set (spacing>3x3 m)

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DEVELOPMENT OF A GENERALIZED GROWTH MODEL FOR MIXED TROPICAL FORESTS OF PENINSULAR MALAYSIA[1]

Wan Razali Bin Wan Mohd and Krishna P. Rustagi[2]

ABSTRACT. Models for predicting diameter growth and non-catastrophic mortality in the mixed tropical rain forests of Peninsular Malaysia by broad species groups are presented. In the absence of quantitative measures of site, density and/or inter-tree competition, the past rate of diameter growth was found to be the most significant predictor of future diameter growth in a weighted linear regression model. The logistic model for predicting tree mortality gave satisfactory results for only two of the four species groups.

INTRODUCTION

The literature on growth and yield of tropical rain forests is sparse, and most of the work so far is preliminary (Wan Razali 1986). The reasons for this are not hard to find. First, there is a continuum of species diversity with the result that no two stands are alike. Second, measures of site productivity, which are taken for granted elsewhere, are almost impossible to quantify. Finally, field work involving species identification, as well as diameter, height and site indicator measurements is not easy. The diameter measurement is complicated by fluting of stems and formation of buttresses, the shape and size of which changes over time. The tops of trees in the upper canopy are not visible which makes measurement of total tree heights difficult. The concept of site index, as applied in temperate forest, is not applicable to mixed tropical forests. Other means of expressing potential measure of site have to be derived. The problems with diameter and height measurements are, perhaps, the main reasons for lack of precision in the volume tables for tree species in the tropical rain forests. The development of growth and yield models for these forests will, therefore, be a slow process.

The study reported here deals with only a small segment of the growth and yield modelling in tropical rain forests. The analytical experience of predicting diameter growth of individual trees and prediction of their non-catastrophic mortality is presented here. The data used came from the tropical rain forests of peninsular Malayasia. Ten-plot clusters, with total area of 0.4 ha (20m x 200m) were used. Only trees 20cm and larger in diameter were measured on all 10 plots. Trees with diameter 10cm or larger but less than 20cm were measured on only 4 plots (20m x 20m each) per cluster. Trees 5cm and larger in diameter but less than 10cm were measured on 8 plots (10m x 10m each).

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1 This paper summarizes results from the Ph.D. thesis by Wan Razali (1986). Presented at the IUFRO Forest Growth Modelling and Prediction Conference, Minneapolis, MN, August 24-27, 1987.

2 Director of Forestry Research, For. Res. Inst. Malaysia; and Assoc. Prof., College of Forest Resources, Univ of Washington.

A total of 54 such clusters were used in this study which had minimum of 3 and in most cases up to 6 measurements. They have been measured at intervals varying from three to nine years. Out of these, 36 were randomly selected and used for model development. The data from the remaining 18 clusters was used for validation purposes.

The number of species in tropical rain forests is large and rarely does a single species constitute more than 10% of the total stand basal area. Therefore, species are generally grouped, based on their growth characteristics and general properties. Four such groups were identified and used in this study. These are:

Dipterocarps (DIPT)
Light hardwoods (LHW)
Medium hardwoods (MHW)
Heavy hardwoods and other misc. spp (HHW)

$\left.\begin{array}{l}\text{Light hardwoods (LHW)}\\ \text{Medium hardwoods (MHW)}\\ \text{Heavy hardwoods and other misc. spp (HHW)}\end{array}\right\}\text{(NON-DIPT)}$

DATA ANALYSIS

In view of the fact that only stem diameter information was available, the dependent and independent variables in the analysis were diameters or their functions. The number of surviving trees by size class was additional information which was also used in the analysis. The analysis was limited to:

a) Prediction of annual or periodic diameter growth. Because of the nature of mixed tropical forests and the management practices used, aggregate basal area growth has little practical use. Trees are harvested using selection system and trees above certain diameter only are harvested. An updated diameter class distribution list, therefore, has definite use in management planning and yield forecasting.

b) Prediction of non-catastrophic mortality. Besides suppression mortality, selection harvest in tropical forests induces mortality in the residual stand, which is not always confined to the smallest trees. Accounting for this mortality is, therefore, essential in updating of stand tables.

Though ingrowth is an important element in stand table projection, it was not part of this study. It was felt that the yield projections will be made only to the end of the next cutting cycle, on which ingrowth would have little impact.

PREDICTION OF DIAMETER GROWTH

There is no conclusive evidence that diameter growth or tree basal area growth perform better as the dependent variable (Hegyi 1973, Lanford and Cunia 1977, Opie 1968 and 1972, Moore et al. 1973, Stage 1973, West 1980, Manley 1981). Preliminary data analysis suggested that diameter growth was a better dependent variable than basal area increment and its logarithm.

As stated earlier, no quantitative measure was available to reflect either the site productivity or the stand density. The tree basal area and various forms of its aggregation were used as independent variables with the hope that these measures would, to some extent at least, indirectly capture the essence of these two important factors in growth prediction model.

The regression models tested included: linear unweighted and weighted models, and weighted nonlinear models. The regression analysis showed that weighted linear regression models performed better than the other two both in terms of mean square of the residual and the homogeneity of variance. Using 'all possible subset' regression program of the BMDP statistical software (Dixon 1983), the following model was finally selected as best for diameter growth for Dipterocarps:

$$\delta D = .149914 + .0205352*D - .0001612*D^2 + .928187*RS - .0011628*GRBA - .0111762*D*RS + .0000108*D*GRBA$$

where

δD - periodic annual diameter growth (cm/year)
D - tree diameter (cm)
RS - ratio of species group basal area to the total plot basal area
GRBA - species group basal area per plot • (dm^2/plot)

All of the above regressors were significant. Multicolliniarity was unavoidable and the R^2 value came out to be only 0.19518 with the standard error of estimate equal to 0.404901cm. Similar expressions were obtained for the other species groups.

The R^2 value is disappointingly low. The scatter-plot of diameter growth over diameter hardly shows any trend. Unless explicit expressions for site productivity, stand density and/or some measure of inter-tree competition within and between species groups, can be quantified and used as independent variables in the regression model, it would be almost impossible to account for large variation in diameter growth.

How much improvement in prediction of diameter increment if past diameter and basal area growth rate are used as a regressor? Using the past annual growth rate in individual tree diameter and basal area, species group basal area and total basal area as lagged variables, improvement in the prediction of tree diameter growth rate was remarkable. Again using linear model and weighted regression (with inverse of diameter squared as weight), the following weighted model was identified as providing the most satisfactory fit for DIPT:

$$\delta D = .1123 + .0085569*D + .0000496*D^2 + .63472*LDG - .0001057*BAT - .0020857*LBAG - .965438E-5*LTBAG + .0001357*D/RS$$

where, in addition to the variables defined earlier,

LDG - annual tree diameter growth rate during the previous measurement period (cm/year)
BAT - total plot basal area (dm^2/plot)

LBAG - annual tree basal area growth rate during the previous measurement period (cm^2/year)
LTBAG - total annual basal area growth of all species per plot during the previous measurement period (cm^2/year)

The R^2 value came out to be .48653 with standard error of estimate 0.3234cm. Similar improvements were noticed in the prediction of diameter growth of other groups, the selected model in each case exhibiting minor differences in the overall model. The past rate of diameter growth fairly well reflects the impact of site productivity and inter-tree competition. Therefore, unless quantitative measures for these variables can be developed, past rate of diameter growth remains the best predictor of future diameter growth in the mixed tropical rain forests.

PREDICTION OF NON-CATASTROPHIC MORTALITY

It was decided to use logistic model with non-linear regression in this study. There were two reasons for that. One, the logistic model ensures that the predicted probibilities are non-negative and do not exceed 1; and two, logistic models generally exhibit improved statistical properties over ordinary linear regression models (Hamilton and Edwards 1976).

In view of the fact that trees with less than 10cm diameter will not be able to reach the 30cm diameter threshold -- the minimum tree diameter currently considered for planning selection harvest during the next cutting cycle -- in less than 20 years, the 5-10cm class would in no way affect the harvesting decisions for the next cycle. Therefore, the modelling for mortality was limited to trees 10cm and larger. Further, as all trees 10cm and larger were measured on only 4 out of 10 plots per cluster, the data from these 4 plots only was used for this analysis.

Three measurements per plot were needed for logistic modelling; the first two measurements provided the diameter and basal area growth, which were used as predictors. The third measurement provided the survival status (dead or alive), which served as the dependent (binary) variable. As each plot-cluster had 3 to 6 measurements, it was decided to use only one set of three measurements per cluster.

The general form of the logistic model is:

$$P(X) = \exp\{U\}/[1+\exp\{U\}] + e$$

where P(X) is either 0 or 1, U is a linear function of independent variables and e is the random component.

The independent variables included both tree attributes, such as D, D^2, δD, δBA, and plot attributes such as GRBA, BAT and RS. Another variable RD was computed as the ratio of total plot basal area to square-root of average diameter to reflect stand density (Curtis 1982). The variables which were significant and showed up in the final model are:

Spp group	Independent variables
DIPT	D D^2 δD and δBA
LHW	D D^2 and RD
MHW	D*RS and RS
HHW	D D^2 δBA and BAT

The logistic model was fitted in a stepwise manner to the data sorted by species group using the program PLR of the BMDP software. Several criteria were used in selection of variables and in the stopping rule. These included: improvement chi-square; Brown's goodness-of-fit test (Prentice 1976); and the t-value. The program PLR generates all these statistics, and based on these criteria, the fitted logistic model appeared satisfactory for DIPT and LHW. The model did not fit the data well for species groups MHW and HHW. No attempts were made to improve the fit for these two groups. The fitted models for each species group showing the regression coefficients and corresponding goodness-of-fit chi-square are given in Table 1.

Table 1: Summary of stepwise logistic regression for Dipterocrps (DIPT) and non-Dipterocarps (LHW, MHW and HHW).

Spp. group	Step no.	Variable Xi	Coeff. bi	t value	Improvement[1] chi-sq	Brown's[2] chi-sq (p-value)	Pearson's[3] chi-sq
DIPT	1	D	-0.145	-5.240	55.55		
	2	D^2	0.001	3.370	28.58	0.491	4.91
	3	δD	-4.262	-4.070	12.23	(0.783)	(ns)
	4	δBA	0.045	3.352	10.81		
		(const)	1.896	3.344			
LHW	1	D	-0.224	-8.880	132.95		
	2	D^2	0.002	6.940	47.04	0.686	9.63
	3	RD	-0.012	-3.260	11.12	(0.710)	(ns)
		(const)	4.640	5.530			
MHW[4]	1	D*RS	-0.303	-7.920	62.28		
	2	RS	8.177	4.630	23.77	3.147	47.32
		(const)	-0.129	-0.540		(0.209)	(**)
HHW	1	D	-0.112	-5.990	47.86		
	2	D^2	0.002	5.630	15.38	1.046	20.47
	3	δBA	-0.025	-3.090	8.05	(0.593)	(**)
	4	BAT	-0.002	-2.230	6.95		
		(const)	2.453	3.880			

1. Improvement chi-sq = 2*[Ln(MLR)]
2. In Brown's test, a large chi-sq or small p-value indicates that the logistic model is not appropriate.
3. (ns) - not significant; and (**) - highly significant.
4. For MHW, D entered the model at step 1 but was subsequently removed by program PLR.

VALIDATION OF RESULTS

There were no indications of negative predictions or signs of unsatisfactory model behavior as judged by the scatter-plot of residuals. Lack of similar growth models in the mixed tropical rain forests, made it impossible to compare our results with any other alternate model.

Checking the predictions against observed results provides a simple and reliable method of judging the validity, reliability and accuracy of the model. The data from 18 ten-plot clusters, which was set aside for this purpose, was used to compare predicted diameter growth as well as mortality against observed values.

Before carrying out comparative analysis of the model, both data sets were examined in detail to identify any dissimilarities. Though relative frequencies of diameter distribution were more or less identical for each species groups in both data sets, there were considerable differences in the distribution pattern of basal area.

VALIDATION OF DIAMETER GROWTH

The following comparisons were carried out between calibration and validation data set:

a. Average of predicted minus observed diameter growth over all trees. This was zero for every species group in the calibration data set and very close to zero for the validation data set. Breakup by plot basal area into low ($\leq$ 650 dm^2), medium (651 - 900 dm^2) and high ($\geq$ 901 dm^2) failed to indicate any significant departures from zero. However, when the trees were classified by diameter class and species group, the validation data set exhibited larger departures from zero.

b. Residual root mean square error. The root mean square error for the validation data set did not materially differ from that for the calibration data. Grouping of the data by low, medium and high total basal area plots did not materially change the results.

c. Observed versus predicted diameter growth. Comparison of predicted with observed diameter growth showed consistency even when the data was grouped by species group and diameter class; as well as basal area level and diameter class. When plotted against RS -- the ratio of species group basal area to the total basal area -- the results were not materially different for both data sets.

In summary, the diameter growth model exhibits satisfactory behavior. The major drawback of the model is that past rate of diameter and/or basal area growth is needed for predicting future diameter growth.

VALIDATION OF MORTALITY MODEL

This was accomplished by carrying out Pearson's chi-squared test on the validation data set. The stem frequency tables with 5 cm diameter classes (10-15, 15-20, etc.,) were prepared using the observed mortality

data from both sets of plots (calibration and validation). The expected frequencies were computed by summing up probabilities using the initial stem frequencies. The chi-square test on the validation data set was insignificant for DIPT, LHW, and HHW, and significant for MHW.

CONCLUSIONS

The results reported here, lack the precision of similar work in the temperate forests and there is considerable scope of improvement and refinement in the two components (diameter growth and non-catastrophic mortality prediction) presented here. Eventually, the ingrowth component must also be incorporated in the model as the long-run stand table projection would not be complete without it.

In the tropical rain forests, the mortality problem is further compounded by damage to the residual stand caused by selective logging. Tang and Wan Razali (1981) have reported that logging induced mortality is a significant component of total mortality in these forests.

This study also brings out problems with and deficiencies in the data which limited the analysis. These issues must be addressed, if meaningful improvements are to be made in the modelling of tropical forests. These include:

1) From the data currently being collected in the research plots, it is not possible to quantify site productivity and density. Both these attributes are known to have considerable influence on diameter growth rate and non-suppression mortality. Soil characteristics, topography and precipitation may be more suitable in characterizing site in these forests.

2) Measurement of tree diameters and heights in the mixed tropical forests require attention. Inconsistencies in diameter measurements were not uncommon. These measurement errors may have made a significant contribution to the poor fit of the diameter growth model.

The problem of modelling growth and yield in mixed tropical forests is too complex and beyond the resources of any one country in the tropical region. A viable alternative would be for these countries to pool their resources under technical guidance of some international agency.

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THE CACTOS SYSTEM FOR INDIVIDUAL-TREE GROWTH SIMULATION IN THE MIXED CONIFER FORESTS OF CALIFORNIA

Lee C. Wensel and Greg S. Biging[1]

ABSTRACT.
The California Conifer Timber Output Simulator, CACTOS, can be used to simulate changes in a forest stand due to growth and harvest. The growth simulation uses an individual-tree model based upon site index curves and species-dependent functions of tree size and competitive position within the stand. The harvest simulator in CACTOS enables the user to simulate thinnings in silvicultural prescriptions. The CACTOS system includes a program to generate missing tree measurements and programs to summarize and compare simulations with actual growth measurements.

INTRODUCTION

Changing age class distributions and changing forest practice rules in California led to the development of a University-industry cooperative research effort to study stand dynamics in uneven-aged, mixed-species young growth forest stands. This effort, started in 1974 with work in the redwood region on California's north coast, was joined by an interior northern California effort in 1978. The initial objective was to build a model to predict the development of forest stands under alternative management strategies. An additional objective was to standardize measurement and sampling procedures to facilitate the pooling of data across ownership boundaries so that future yield studies would have a credible data base.

The forests of northern California are characterized by stands of mixed species as well as mixed ages and sizes. "Mixed conifer" describes forest stands that are at least 80 percent conifer with no single species comprising more than 80 percent of the stand by volume. The other conifer stand types recognized here are Douglas-fir, ponderosa pine, and true fir. While the first two stand types, Douglas-fir and ponderosa pine may occur in even-aged stands, they are usually of uneven ages and sizes, the product of years of harvesting merchantable timber and leaving the smaller trees as growing stock. These stands were allowed to remain uneven-aged, rather than converting them plantations, but California foresters have only had limited experience to guide them in making optimum silviculture prescriptions. How would the existing stands develop under alternative levels and types of thinnings and partial harvests? In the absence of cutting trials, a model was needed to explore this question.

Working with the industry members of the Northern California Forest Yield Cooperative, the California Conifer Timber Output Simulator, CACTOS, was developed to meet this need (Wensel and others, 1986). The objective here is to introduce the CACTOS System, that is the simulator and its supporting programs, and to discuss it's modelling approach. The operation of the CACTOS System for MS-DOS personal computers will be

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demonstrated in the poster session and sample output is given in these proceedings (Meerschaert 1987).

THE CACTOS SYSTEM

The CACTOS System includes the simulator, CACTOS, and a number of utility programs that prepare data for CACTOS and to summarize the results for multiple plots within a given stand. The general flow of information in the CACTOS System, illustrated in Figure 1, starts with providing CACTOS with a representation of the stand to be simulated. If individual measurements, or all measurements for a variable (except species and DBH), are missing, the stand generator, STAG, is used to complete the representation[1] CACTOS then simulates the sequence of 5-year growth cycles, with or without intervening thinnings. This produces a yield stream for each stand description / silviculture alternative chosen. These yield streams can then be averaged using the yield averager, YDAVG, to form a yield summary for all plots in a given stand. For cases where yield data are available from actual field trials, the program COMPARE facilitates the comparison of predicted yields with actual yields.

Central to this system is the representation of the stand to the simulator. This is discussed below, followed by a description of the components of the CACTOS System and its modelling philosophy.

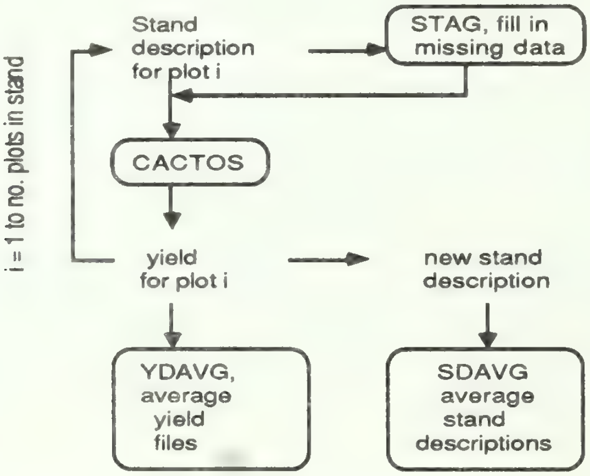

Figure 1. Structure of the CACTOS System

STAND DESCRIPTION

The stand descriptions used in the CACTOS System includes both plot and individual tree components. At the plot level, stand productivity is expressed by listing the site indices for all species present. This is important because the competitive advantage of one species over another varies from one area to another. In addition, age may be added for any species where it is a relevant label (say, for any even-aged stand component). For tree information, the varied sizes and uneven ages of the forest stands require that the stands be

[1] STAG is described further in these proceedings (Biging and Wensel 1987)

described for modelling by the inclusion of both diameter and crown information. Thus, the stand description used by CACTOS has the following tree information: species, diameter at breast height (DBH), total height (H), height to the crown base (HCB) or live crown ratio (LCR), and number of trees per acre (TPA) represented by each tree.

While the location of the tree would complete the 3 dimensional stand description, tree coordinates are generally not available in operational inventories. Thus, the only locational information used is that the trees are assumed to be on the same sample plot, an assumption that invalidates averaging plots to get an average stand description for growth simulation.

PROGRAM STRUCTURE

As illustrated in Figure 2, the simulation operations carried out by CACTOS are of two types: growth projection and harvest simulation. In addition, report generation and a number of utility operations can be performed. Growth is simulated in 5-year cycles and optional harvests (thinnings) can be done in any of the 5-year intervals. The various reports are used to provide the user with important data summaries to be used in choosing the alternatives to be simulated and to record the results of the simulation. All commands to the simulator are issued by typing two-letter commands in response to computer prompts. Alternatively, commands can be put into a command file for batch processing of multiple stands with the same prescription or for multiple prescriptions.

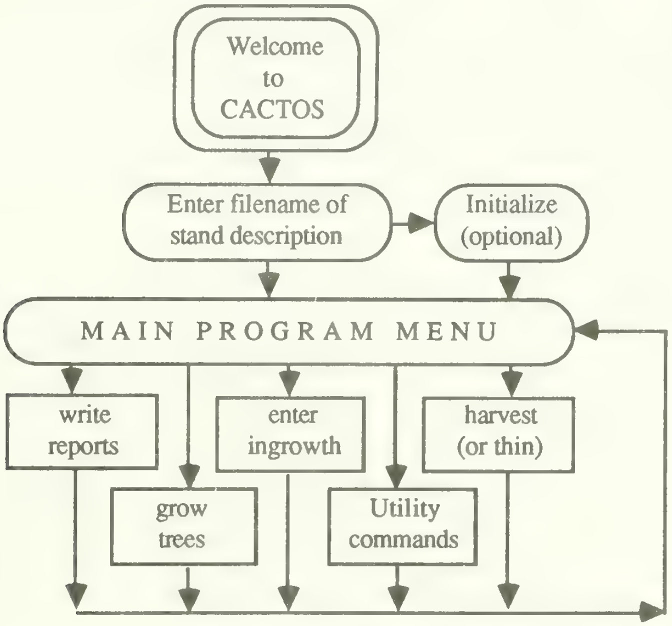

Figure 2. Structure of CACTOS, the California Conifer Timber Output Simulator

GROWTH PROJECTION

In each of the 5-year growth cycles the current tree height and diameter growth are computed as a product of the tree's potential growth times a factor based upon the competitive position of the tree in the stand (Wensel and others, 1987). This process is similar to that used by a number of researchers (see Monserud 1975, Belcher and others 1982, and Krumland 1982.) The approach used to model height growth and DBH growth are similar. Both have potential and competition components and they use similar theoretical model forms. However, the data bases for the models are different and they were fitted

The growth models used in CACTOS continue to evolve as additional data become available. For individual users, these data can be used to develop calibration factors to be entered into CACTOS. However, we expect to use the latest remeasurement of our network of permanent plots to completely reestimate the growth rates, including localizing the estimates, where necessary, and testing alternative model formulations.

MORTALITY

The current estimates of mortality in CACTOS are now just "borrowed" from CRYPTOS (Wensel and others 1987a) and can be turned on and off at will. While one could argue that this is of little importance in heavily managed forest stands, it is currently a weakness that we hope to remedy with the permanent plot remeasurement data that we are now getting from our industry cooperators. However, mortality estimates will require additional user input because mortality is a very local phenomenon.

HARVEST

The ability to simulate various thinning procedures is an important part of any timber output simulator. Since the stand description contains tree height and height-to-the-crown-base information as well as DBH, it is possible to simulate rather involved thinning prescriptions. CACTOS has 4 alternative cutting routines that can be invoked in any one of the 5-year cycles. These include cutting with (1) DBH control, (2) basal area control, (3) a "free" cut, and (4) a sanitation cut. While under DBH control, one can cut (or retain) all or any proportion of the trees in any DBH class or range of classes. Under basal area control, the user may specify the basal area to cut (leave) and can mimic a cut from below or from above based upon a function of the DBH and LCR. The "free" cut allows the user to create up to 24 variable-width diameter classes and harvest in any of these classes, selecting trees according to DBH and LCR. Finally, the sanitation harvest removes the trees with LCR less than or equal to the user-specified LCR. The "free" cut or the sanitation harvest may be used in lieu of simulated mortality to give the user greater control over the trees that are "killed". There is a problem, however, in matching simulated thinnings to actual thinnings where trees that are not in the prescription are cut because they are in the way. On the ground the prescription would be altered to account for this. Also, thinning to achieve specified spacings cannot be effected with distance-independent models.

DISCUSSION

Users have found the CACTOS system easy to use, largley because it was designed with a lot of help from users who were computer novices. It is easy to run a stand description through a variety of silvicultural precriptions in a "game" atmosphere. In fact, the users tend to get carried away and push the system far beyond its designed limits. Thus it is important to note that CACTOS is also designed with the ability to calibrate projections with local growth data, making the final projections the responsibility of the user.

Experience with the CACTOS System and other simulators coincided with changing economic conditions in the forest industry. This led to pressure for extension of the original objectives to include a system for making the economic evaluations necessary to evaluate management strategies for both short and long range planning. Here the forest manager is faced with the problems of predicting the growth and future yields of forest stands under a number of alternative management strategies over a rotation or over an entire planning horizon or cutting cycle. These predictions are then evaluated to estimate the economic and other returns for each strategy by applying prices, penalties, or both to the yield estimates. Aggregating these alternative returns for all forest stands in the forest is then the basis for finding the optimum strategy to best meet the forest management objectives of the ownership.

However, CACTOS was designed as an interactive system and, in this mode, the user can exercise some judgement in selecting the operations to be applied to each stand. We have extended CACTOS to permit "batch" operation to generate multiple stands to be operated on by multiple silvicultural prescriptions. This places additional responsibility on the user to ensure that the combinations of growth, mortality, ingrowth, and thinning prescriptions that are applied to each stand prescription are reasonable. In fact, what is needed is an "expert system". Professors Larry Davis and Keith Gilless are leading efforts to use the output of the CACTOS system to develop the econòmic planning models. This extension points to the crying need for reliable, accurate, and robust yield models.

The CACTOS System continues to evolve as our data bases mature and our understanding of the system crystalizes. While tests have shown that the growth estimates are unbiased with respect to tree size but the growth rates for plantations, are under estimated and the estimates still need to be localized to improve the accuracy of the predictions. Also, there is still insufficient response information to know how well it predicts the effect of release.

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SOFTWARE

Program name: The CACTOS System, including programs CACTOS, STAG, YDAVG, SDAVG, COMPARE

Programmers: Greg S. Biging, Kenneth Brown, Peter J. Daugherty, James R. Koehler, Bruce E. Krumland, Walter J. Meerschaert, Mark E. Teply, Tim A. Robards, Paul Van Deusen, and Lee C. Wensel

Hardware and software requirements:

IBM PC or compatible, with math coprocessor

Operating system	DOS 3.0 or higher
Memory required	512 k
Disk drives required	2 floppies or hard drive
Printer required	no; output is to disk for later printing, to the screen, or both

Apple Macintosh 512, Plus, or SE

Operating system	Finder 3.0 or higher
Memory required	512 k
Disk drives required	2 floppies or hard drive
Printer required	no; output is to disk for later printing, to the screen, or both

Additional information: Developed at the University of California in cooperation with the Northern California Forest Yield Cooperative

Program available from:
The Biometrics Program
Department of Forestry and Resource Mgt.
University of California
Berkeley, CA 94720

Media: floppy disks and user's manuals

Cost: $125, checks payable to Regents, University of California

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REPRESENTING SITE QUALITY IN INCREMENT MODELS:
A COMPARISON OF METHODS

William R. Wykoff and Robert A. Monserud[1]

ABSTRACT. Alternative site measures were compared by fitting separate diameter increment models to Douglas-fir increment data from the northern Rocky Mountains. The first model used site index while the second used habitat type and abiotic site descriptors such as elevation, slope, aspect, and location to express site productivity effects. The models were compared by analyzing prediction errors for an independent collection of long-term permanent plots. The models behaved similarly and explained about the same amount of variation in diameter increment.

INTRODUCTION

The Quixotic search for a single measure that integrates the effects of soil and climate on tree growth continues to be a primary focus of mensurational research. More often than not, the variable of choice has been site index, and it has proven to be an effective predictor of tree growth in numerous growth and yield studies.

The Prognosis Model (Stage, 1973; Wykoff et al., 1982) was developed to represent a forest region that is characterized by a great deal of variability in species and age composition in both natural and managed stands. Frequently, suitable site trees are not available. Further, proper application of site index requires accurate age determination. Age may be expensive to inventory when stands are not even-aged or date of stand origin is unknown. Monserud (1984a) has summarized other problems with site index. Some of these will be mentioned in passing.

Partly as a result of the above considerations, the Prognosis Model is one of the few examples of a growth model that does not use site index as a predictor variable. Instead, site descriptors such as habitat type, location, elevation, slope and aspect are directly incorporated in the prediction equations. The assumption that site effects are adequately represented without site index has been frequently disputed but never directly tested.

The objective of this study was to compare two disparate approaches for incorporating site effects into growth models. The first approach (which is used in Prognosis) eschews site index, relying instead on a linear combination of habitat type and several abiotic site descriptors (elevation, slope, aspect, location). The second approach (termed Potential and Modifier) relies on site index to determine the maximum growth possible; this potential is then modified (or reduced) by incorporating non-site effects due to tree size and stand density.

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METHODS

Alternative diameter increment models were fit to individual Douglas-fir (Pseudotsuga menziesii var. glauca [Beissn.] (Franco) trees sampled in a Douglas-fir site index (DFSI) study (Monserud, 1984b). The models were evaluated by comparing performance on an independent sample of Douglas-fir from the Intermountain Research Station's permanent sample plot (PSP) collection (Haig, 1932).

For comparative purposes, residuals were computed and evaluated for both the PSP and DFSI datasets using the diameter increment model implemented in version 5.2 of the Prognosis Model (NI52) (Wykoff, 1986). Parameters for NI52 were estimated from a larger data base (N=12313) combined from the USDA Forest Service Northern Region timber management inventory and a research study of young, managed stands.

THE DATA

DFSI--The 135 DFSI study sites are distributed throughout northern Idaho and western Montana and sample a variety of forest types. The selected stands are generally composed of mixed species and multiple-age classes, although roughly a third are even-aged. Site selection was not constrained by stand structure but was based only on availability of suitable Douglas-fir site trees. In addition, a conscious effort was made to avoid geographic clustering of the study sites. The sampling framework is therefore ideal for developing a model that can be generally applied to the proscribed region.

Habitat type, slope (SL), aspect (ASP), National Forest, and elevation (EL) were recorded for each DFSI study site. In addition, each site was sampled with a cluster of four 20 basal area factor (baf) variable radius plots, and all "in" trees were measured for diameter breast height (DBH), species, crown ratio (CR), height, and 10-year diameter increment (DG). Increments were measured from increment cores, and Douglas-fir site index (SI) was determined by stem analysis of selected site trees. Crown competition factor (CCF) (Krajicek et al., 1961), stand basal area (BA), and the distribution of tree basal areas (PCT) were derived from the point sample inventory and backdated to the start of the growth period using the procedures described by Wykoff et al. (1982).

PSP--The permanent sample plots are concentrated in the Priest River and Deception Creek Experimental Forests in northern Idaho. Composition of the stands varies widely, but generally four to six species are present. At the time of plot establishment, at least 15 percent of the stems were in an essentially even-aged western white pine (Pinus monticola Dougl.) component. Because of accelerated mortality of white pine due to blister rust and succession to more tolerant species, the current age and species structure of these stands is quite complex.

The permanent sample plots have been remeasured at 5- or 10-yr intervals since the time of establishment. To minimize serial correlation and confounding due to variation in climate, only the measurements for the

10-yr period that most closely corresponded to the decade sampled by Monserud (1966-1976) were used. Inside-bark (ib) diameter increments were computed by subtracting successive DBH measurements and adjusting for bark thickness (assuming an ib/ob ratio of 0.867; Monserud, 1979). White pine site index was determined at the time of plot establishment using Haig's (1932) method. Steele and Cooper's (1986) relationship was used to estimate Monserud's site index from white pine site index for the PSP data.

The PSP data provide a good test of the extrapolative capabilities of the models. The stands in this sample have lower site indices and higher basal areas, and the Douglas-fir are smaller in diameter, have much smaller crowns, and generally occupy more subordinate positions in the canopy. In contrast to the DFSI plots, which all contained dominant Douglas-fir, only 35 of the 102 permanent sample plots had any living Douglas-fir at the last measurement, and in only 14 of these plots were the Douglas-fir in dominant crown positions.

ANALYSIS

The first model (NIDFSI, eq. 1) is styled after the regression model that is implemented in the Prognosis Model (Wykoff 1983, 1986). The dependent variable in this model is the natural logarithm (ln) of periodic change in squared diameter (DDS).

$$\begin{aligned} \ln(DDS) = {} & HAB + LOC + b_1 \cdot \ln(DBH) + b_2 \cdot DBH^2 + b_3 \cdot BAL \\ & + b_4 \cdot BAL/\ln(DBH+1) + b_5 \cdot CR + b_6 \cdot CR^2 + b_7 \cdot CCF \\ & + b_8 \cdot SL \cdot \cos(ASP) + b_9 \cdot SL \cdot \sin(ASP) + b_{10} \cdot SL + \\ & + b_{11} \cdot SL^2 + b_{12} \cdot EL + b_{13} \cdot EL^2 \qquad (1) \end{aligned}$$

where

b_1-b_{13} are regression coefficients,
LOC = intercept dependent on plot location (National Forest),
HAB = intercept dependent on habitat type,
BAL = estimate of stand basal area represented in trees that are larger than the subject tree,
and all other variables are as previously defined.

Site index is not used in this model, but site effects are incorporated by using intercepts that are dependent on habitat type and location, along with transformations of elevation, slope, and aspect.

The second model (POTMOD) is a potential-and-modifier model similar to that described by Hahn and Leary (1979) and Holdaway (1984). This style of model was selected for comparison because it uses site index in a theoretically appealing manner. In our formulation, potential (eq. 2) is a function of site index and diameter at the start of the growth period. This model form produces a flexible unimodal curve that can readily assume the shape of a typical increment curve (Wykoff, 1983).

$$POT = c_0 + \exp(c_1 + c_2 \cdot \ln(DBH) + c_3 \cdot DBH^{c_4}) \qquad (2)$$

where

POT = potential DDS,

and $\{c_0 - c_4\}$ are site index dependent parameters.

The modifier (eq. 3) is a function of diameter, crown ratio (CR), and basal area in larger trees (BAL).

$$MOD = c_5/[1.0 + \exp(c_6 + c_7 \cdot DBH + c_8 \cdot BAL + c_9 \cdot CR)] \quad (3)$$

The resulting prediction is the product of these two submodels:

$$DDS = POT \cdot MOD \quad (4)$$

Note that the intent was to isolate all site effects into the potential function. Although simple in concept, the overall model (4) is complex and the fitting procedure approaches the mystical. The fact that the true potential is never observable is a considerable complication.

Models (1) and (4) were compared by evaluating the magnitude and distribution of residuals for the test dataset on two scales. The diameter increment scale was selected because it can be readily visualized. However, for statistical comparisons, residuals on the ln(DDS) scale are a better measure because the variance of the distribution of these residuals is more nearly independent of the predictor variables.

RESULTS AND DISCUSSION

When the potential function in POTMOD was fit to the data for site classes, all of the parameters exhibited trends relative to site index (Table 1). There is no doubt that a more parsimonious representation of the relationship could be developed. However, the behavior of the model for feasible values of SI and DBH appears acceptable. Potential is unimodal relative to DBH and increases with increasing SI. Keep in mind that potential is a mental construct that cannot be observed. The purpose of specifying a potential is to identify a reasonable, albeit arbitrary, standard for evaluating the effects of competition and vigor. While not elegant, the model as formulated provides such a standard.

TABLE 1. Final estimates for the POTMOD coefficients.

Potential coeff. (eq. 2)	Value	Modifier coeff. (eq. 3)	Value
c_0	$\exp[-20.94 + 5.41 \cdot \ln(SI)]$	c_5	1.8
c_1	$-0.34415 + 0.04575 \cdot SI$	c_6	2.4553
c_2	$1.225 - 0.003 \cdot SI$	c_7	0.0214
c_3	$-0.000152 \cdot \exp(0.0582 \cdot SI)$	c_8	0.0056
c_4	$2.425 - 0.015 \cdot SI$	c_9	-1.4279

When attempts were made to simultaneously estimate all parameters of the modifier function, the regression would not converge. Constraining c_5 to slightly exceed the largest ratio of observed to potential DDS produced rapid convergence. The coefficients thus estimated for BAL, DBH, and CR in (3) are highly significant and have reasonable signs.

When parameters were estimated for NIDFSI (eq. 1), the coefficients for CCF were nonsignificant. A correlation between site and density was suspected (good sites should be capable of supporting more biomass than poor sites, and in undisturbed stands a natural correlation between site and density could result). However, in a simple linear regression, site index explained less than 1 percent of the variation in CCF for the DFSI data. Thus, other model parameters were estimated holding CCF coefficients at the NI52 values. All other effects were significant and coefficients had acceptable signs.

A comparison of the model used in Prognosis (NI52) with the version fitted to the DFSI data (NIDFSI) revealed two general differences. Whereas the effects related to tree size, competition, and vigor appear to be expressed more strongly in NIDFSI, site effects are more important in NI52 (Table 2). The data used to estimate NI52 parameters were considerably more extensive than the DFSI sample and included a wider range of forest types with greater diversity in stand structure.

TABLE 2. Coefficients for NI52 (Wykoff, 1986) and NIDFSI (Model 1). Habitat and location effects are shown only for habitat type 520 (*Abies grandis/Clintonia uniflora*) on the Clearwater National Forest. NIDFSI contains 11 additional coefficients that represent other combinations of location and habitat type. Coefficients assume that BAL, CCF, and EL have been divided by 100.

	Coefficients			Coefficients	
Variable	NI52	NIDFSI	Variable	NI52	NIDFSI
ln(DBH)	0.5689	1.0452	sin(ASP)•SL	0.0629	0.0402
CR	2.0685	2.9197	SL	0.7818	0.6641
CR^2	-0.6236	-1.3466	SL^2	-1.1238	-1.1435
BAL	0.5020	-0.2526	CCF	-0.0905	-0.0905
BAL/ln(DBH+1)	-2.1159	-0.7615	DBH^2	-0.0004	-0.0008
EL	0.0259	0.0022	Habitat type	0.4778	-0.1561
EL^2	-0.0004	-0.0002	Location	0.5036	0.2168
cos(ASP)•SL	-0.0456	-0.1226			

NIDFSI and POTMOD residuals for the DFSI data were unbiased on both the DG and the ln(DDS) scale and showed no significant trends relative to any predictor variables (Tables 3 and 4). Of particular interest, site index explained only 1.8 percent of the residual variation (0.6 percent of the total variation) in NIDFSI ln(DDS) predictions. Obviously, the addition of a site index term to the explicit site variables already in the model would not improve model performance.

TABLE 3. Proportion of variation explained by alternative models.

	Proportion of variation explained			
	DFSI data		PSP data	
Model	DG	ln(DDS)	DG	ln(DDS)
POTMOD	0.352	0.628	0.295	0.629
NIDFSI	0.365	0.658	0.267	0.593
NI52	0.244	0.595	0.333	0.646

TABLE 4. Proportion of variation in residuals explained by tree and stand variables by simple linear regression [ln(DDS) scale].

		Proportion of variation explained by						
Data	Model	ln(DBH)	SI	PCT	EL	CR	BAL	Age
DFSI:	POTMOD	0.001	0.012	0.005	0.007	0.009	0.002	0.000
	NIDFSI	0.000	0.018	0.004	0.000	0.000	0.000	0.006
	NI52	0.039	0.016	0.106	0.006	0.008	0.076	0.007
PSP:	POTMOD	0.034	0.118	0.059	0.155	0.002	0.035	0.020
	NIDFSI	0.007	0.052	0.008	0.204	0.068	0.000	0.002
	NI52	0.065	0.004	0.079	0.045	0.004	0.042	0.001

Because NI52 parameters were not optimized for the DFSI data, predictions were not as well behaved. On the average, predicted DG was 0.2 inch greater than observed DG, and there were significant diameter and relative size trends. Again, however, site index explained little of the residual variation.

Although there was some degradation in fit, POTMOD and NIDFSI extrapolated reasonably well to the PSP data (Tables 3 and 4). Poorer performance may be partly attributed to the methods by which increment data were collected. The PSP increments were determined by subtraction of successive diameter tape measurements, whereas the DFSI increments came from cores read on a microscope. Partially as a result, the PSP data were almost a quarter more variable than the DFSI data--0.89 vs 1.09 for variance of ln(DDS).

Of note is the apparent importance of site index and elevation for explaining residual variation in both the POTMOD and NIDFSI predictions for the PSP data (Table 4). The marked difference in stand structure

between the studies was probably incorporated in the site effect, and model extrapolation was thus inhibited. NI52 was fit to a more general and far larger data base and the PSP residuals for NI52 are more nearly independent of site effects. Regardless of how site is represented in the model, the data used to develop the model must reflect the range of conditions for which the model will be applied.

CONCLUSIONS

In spite of their diverse origins, the alternative models exhibit remarkably similar behavior. The actual shapes of the increment curves differ somewhat, but both model forms correspond to accepted growth theory. The trends relative to basal area, crown ratio, relative size, and DBH are in accordance with expectations (Figure 1). Given the large amount of unexplained variation in the data, differences in curve form were expected. The rather close correspondence is somewhat surprising.

The collection of site variables used in NIDFSI and NI52 appear to represent site effects about as well as the POTMOD formulation that is based on site index. The models explain about the same amount of total variation in diameter increment, and little of the residual variation is associated with site effects. Although the number of parameters could probably be reduced, the POTMOD potential function gives evidence to the complexity of site effects; many parameters were required to elicit the desired site index-related model behavior.

Decisions on representing site effects should be based on availability of site measures that can be faithfully reproduced using standard inventory procedures. Site index makes a lot of sense for plantations and monocultures, but it makes less sense for the irregular stand structures typical of northern Idaho.

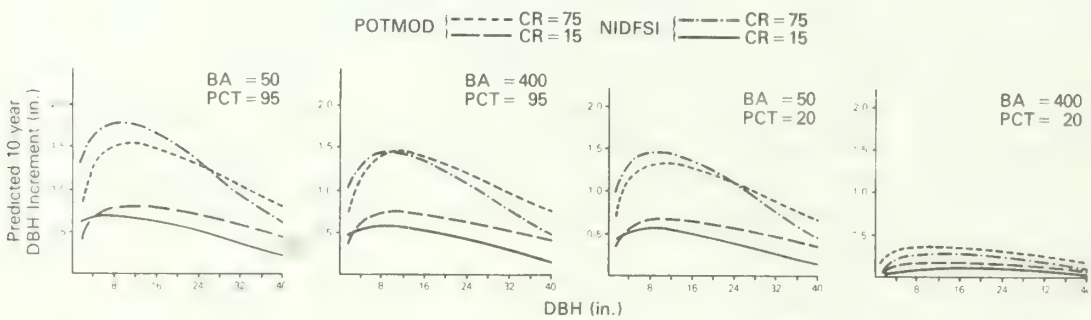

FIGURE 1. For both NIDFSI and POTMOD, predicted diameter increment is unimodal relative to DBH. As stand density increases, increment slows; the increase in density affects the growth of suppressed trees more than it affects dominant trees. Regardless of density or relative size, trees with large crowns grow faster than trees with small crowns. Predictions are for a *Thuja plicata*/*Clintonia uniflora* habitat type on the St. Joe National Forest. Site index is assumed to be 70.

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PREDICTING STEM DIAMETER DISTRIBUTIONS
FROM
GROWTH PROBABILITY EQUATIONS

G.M. Bonnor and S. Magnussen[1]

ABSTRACT. One method of predicting stem diameter distributions for unevenaged forest stands is to develop empirical growth probability matrices based on past growth, and apply them to current diameter distributions. The purpose of this paper is to determine if this matrix approach can be improved by deriving growth probability values from equations in which growth probability is functionally related to stem diameter.

Using permanent sample plot data from an unevenaged, mixed forest in Eastern Ontario, the relationships between five-year growth probability and 1 cm stem diameter classes was explored. It was found that such relationships could be expressed by simple first- or second-degree polynomials, or by constants.

Growth probability equations were calculated by major species groups, and the values derived from them were used to project stem frequencies and volumes from 1985 to 1995.

While the absence of long-term basic data prevented an assessment of accuracy, the method proved to be feasible and yield good results.

INTRODUCTION

As intensive forest management in Canada increases, so does the need for better information about the forest. One such type of information is the growth and predicted future yield of the forest. Many different types of models have been developed for making such predictions. This paper focusses on diameter distribution models using probability matrices. In this approach, growth probability matrices showing the growth and mortality of trees by diameter classes are constructed from past growth

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records and applied to current diameter distributions to yield future distributions. The Markov model provided an early theoretical framework and was used by a number of investigators (Bruner and Moser, 1973; Roberts and Hruska, 1985). Others (Buongiorno and Michie, 1980; Harrison and Michie, 1985; Michie and Buongiorno, 1984) used the probability matrix approach successfully without the constraining assumptions. This approach was also adopted by the present authors (Bonnor and Magnussen, 1986) in their prediction and analysis of growth and yield of unevenaged mixedwood forests in Eastern Ontario; the probability matrices for individual species showed, by diameter class, the probability of a tree dying, stagnating, or growing 1, 2 or more classes of 1 cm each. We noted that, where few trees were sampled, the probabilities for adjoining diameter classes often differed considerably. This may be explained as follows: The true probability of a tree in a given diameter class growing 2 cm may be 0.37 meaning that, on the average, 37% of all trees in that class will grow by 2 cm. Now, if only one tree is sampled in this class, the probabilities can only be 0 or 100. If two trees are sampled, the possible values are 0, 0.50 or 1.00, and so on. Thus, the fewer trees sampled, the poorer the chance of making the correct estimate. Further, while the probability of one class may be 0, that of an adjoining class also with few samples may be 1.00. Such extreme values or shifts in value are unlikely to reflect reality. A possible but expensive solution to this problem is to increase the sample size dramatically. The alternative that we propose is to make use of the expected correlation between adjoining diameter classes: if the probability of a given class is 0.37, that of the adjoining classes can be expected to be near 0.37, not 0 or 1.00.

Thus, the purpose of this study is to develop, for undisturbed, mixed, unevenaged forests, probability equations to predict stem diameter distributions. Also, to present an example of the practical applications of the method. The study is focussed on the development of equations for predicting survivor growth and mortality; ingrowth is not considered.

The concept and initial work of the study has been presented at a 1986 workshop (Bonnor and Magnussen, 1987). Another recent study using the equation approach is described by Solomon et al. 1986. They include stand basal area in the probability equations and account for thinning effects. While no statistics are given for the equations, the 15-year predictions show good accuracy. Ingrowth is difficult to predict accurately and is accounted for in a separate model.

METHODOLOGY

The basic data came from federal forest lands located in the L. 4C Middle Ottawa Section of the Great Lakes-St. Lawrence Forest Region (Rowe, 1972), near Petawawa, Ontario. The main species were white pine (Pinus strobus L.), aspen/poplar (Populus L.), red pine (P. resinosa Ait.), and red oak (Quercus rubra L.). Stands were predominantly of mixed species and unevenaged.

Two sources of data were used:

(1) A 1980 management type of inventory. The primary data source was 341 circular sample plots of 400 m², selected by simple random sampling. Of these plots, 114 were permanent sample plots (PSP's), the balance temporary sample plots (TSP's). In each plot, trees 8.1 cm in diameter at breast height (dbh) and larger were measured for dbh and their species noted. Heights were measured on a subsample of 6-10 trees per plot.

(2) A 1985 re-measurement of the PSP's. Of the 114 plots, 11 were found to have been disturbed, by harvesting or windfall. They were excluded from further analyses.

Additional details on the data sources and the forest are given in Bonnor and Magnussen (1986).

The basic plot data were checked and verified, then grouped by species . Average dbh for the nine resulting species groups ranged from 14 cm (for maple) to 23 cm (for white pine). Maximum dbh was 79 cm. Within each species, the trees were next grouped by 1 cm dbh classes and two calculations were made:

- for the combined PSP and TSP trees, stem diameter distributions were derived showing number of trees per hectare, by species and diameter class;

- for the PSP trees, dbh growth of survivor trees was calculated for the 1980-85 period, and mortality was compiled from the number of trees that died during that period.

The following growth classes were established next:

Survivor growth:	class 0:	tree growth of 0-0.5 cm (stagnation)
	class 1:	tree growth of 0.6-1.5 cm
	class 2:	tree growth of 1.6-2.5 cm
	class 3:	tree growth of 2.6-3.5 cm
	class 4:	tree growth of 3.6 cm or more
Mortality:	class M:	tree died

Finally, for each dbh class and species group, the proportion of trees belonging to the above growth classes was calculated. This proportion was used as an estimate of the probability of future growth. For simplicity, values were expressed on a percentage basis.

The basic tree data were also used to construct local tree volume equations from normal equations using the model developed by Honer et al. (1983) and local height-diameter equations (Bonnor and Magnussen, 1986).

Having thus completed the initial data compilations, a series of scattergrams were produced to assess the nature of the relationship between growth probability, dbh class and growth class. An example is given, for white pine, growth class 1, in Figure 1. For example, the topmost plotted value shows that, in dbh class 13 cm, the probability of a tree growing by 1 cm during a five-year period can be expected to be

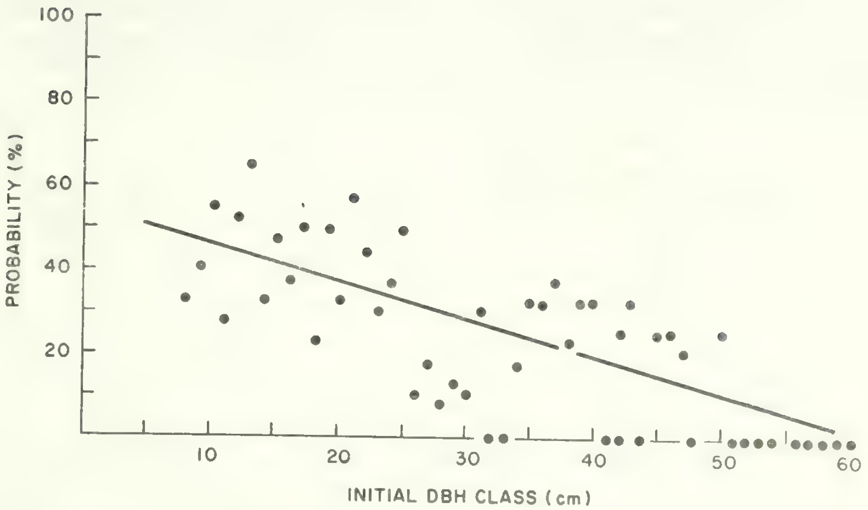

Figure 1. Relationship between growth probability and dbh class for growth class 1, white pine.

.65, or 65% of all trees in the class can be expected to grow by 1 cm. The figure shows a considerable variation in probability values, as expected, but also a definite linear trend: probabilities decrease with increasing dbh.

Similar scattergrams were plotted for other growth classes and species. Analyses indicated that fairly simple models, e.g. first- or second-degree polynomials, described the trends sufficiently well. As an initial step in the regression analysis, such second-degree polynomials were therefore fitted to the data. Weighted regression was used, the weights being the number of trees in the class up to a maximum of 10. The procedure (joint simultaneous regression using dummy variables) was subject to the constraint that, for each diameter class, the probability values of the growth classes had to add to 100%. Thus, for each species,

$$P_i = a_i + b_i D + c_i D^2$$

where i = growth class = 0, 1, 2, 3, 4, M;
P_i = probability value for growth class i (%);
D = diameter class (cm); and
a_i, b_i, c_i = regression coefficients for growth class i, with
$\Sigma a_i = 100$, $\Sigma b_i = 0$ and $\Sigma c_i = 0$

The results were next analysed statistically (using SAS computer software) and inspected visually. The latter revealed - for equations with a decreasing trend - negative probabilities associated with the larger diameters. Accordingly, upper limits (Table 1) to the regression procedure were established and observations beyond these limits were deleted from the data set. Less than five percent of observations for

each species were thus deleted. The data were re-run and a new final set of equations resulted (Table 1). Beyond the diameter limit a constant probability, equal to that derived from the equation at the limit, was used. As an example, the equation for white pine, growth class 1, is shown on the Figure 1 scattergram.

TABLE 1. GROWTH PROBABILITY EQUATIONS

	Growth Class																		Multiple Correlation Coefficient	Upper Limit
	0			1			2			3			4+			M				
	Equation Coefficients																			
Species	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	(R^2)	(cm)
White Pine	17 06	-0 291	-	55.61	-0.933	-	19 29	0.363	-	5.24	0.570	-	-	0.318	-	2.80	-0.025	-	0.58	59
Other Pine	41.87	-1.05	-	35.11	0.440	-	5.93	0.610	-	8.54	-	-	7.53	-	-	1.02	-	-	0.56	39
Spruce	20 04	-	-	43.99	-	-	22.27	-	-	9.12	-	-	4.58	-	-	-	-	-	0.47	53
Other Conifers	-	0 95	-0 023	30.27	1.52	-0.070	51.45	-2 47	0.093	10.40	-	-	5.33	-	-	2.55	-	-	0.68	30
Aspen/Poplar	4 80	-	-	36.12	-0.17	-	31.33	0.17	-	15.70	-	-	2.73	-	-	9.32	-	-	0 56	44
Red Oak	30 20	0 91	-	-15.15	6 14	-0.108	19.91	-1.54	0.050	0.95	-	-	-	-	-	64.09	-3.69	0.058	0.84	33
Maple	19.74	-	-	69.36	-0.95	-	-	0.95	-	3.50	-	-	-	-	-	7.32	-	-	0 78	30
White Birch	42.95	-0.77	-	50.39	-0.22	-	-10.24	1.36	-	-	-	-	-	-	-	16.90	-0.37	-	0.71	34
Other Hardwood	21 07	-	-	54.52	-1.08	-	15.53	-	-	11.14	-	-	2.78	-	-	-5.04	1.08	-	0.52	26

Model $P = a+bD+cD^2$ where P = probability value (%)
D = diameter class (cm)
a, b and c - regression coefficients

For each species, the equations were now used with the 1980 stem diameter distribution to produce stem diameter distributions for 1985, 1990 and 1995. The procedure was similar to that used with probability matrices (Bonnor and Magnussen, 1986) in that the 1980 diameter distribution vector was multiplied by the probability matrix to yield a 1985 diameter distribution vector, and so on. The difference was that values of the probability matrix were derived from the equations.

Next, the new stem diameter distributions were applied to the local volume equations, and volume and stem frequency summaries prepared for 1985, 1990 and 1995.

RESULTS

As shown in Table 1, nine species groups were included in the data set, and calculations were made for all nine groups. However, in the interest of clarity and brevity, many of the results are given only for the dominant species, white pine.

Figure 2 shows, for white pine, the relative magnitude of the growth probability classes derived from a cumulative plotting of the equations. Mortality is low and relatively constant throughout the diameter class range; stagnation and 1 cm growth are high at the lower diameters but low at the upper diameters, while 2, 3, and 4 cm growth are the reverse. Overall, a growth of 1 or 2 cm is most common at the lower diameters and a growth of 2 or 3 cm is most common at the upper diameters.

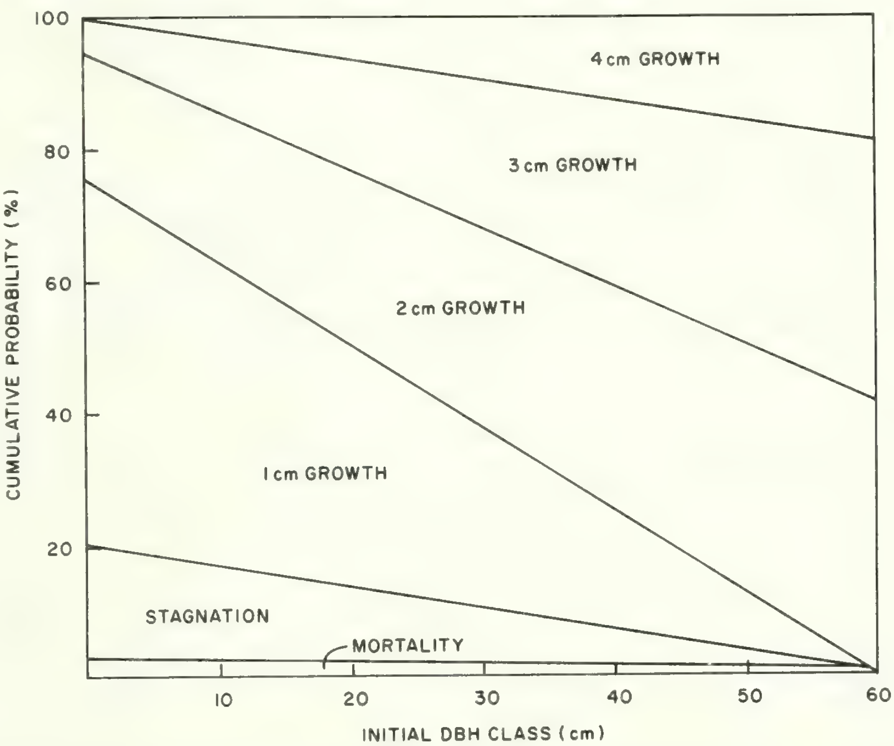

Figure 2. Variation in growth probability with tree diameter for white pine.

Frequency distributions (Figure 3) show, as expected, a general shift to the right between 1985 and 1995. This shift includes several irregularities in the 1985 distribution, one of which (at 30 cm dbh) accounts for a higher frequency in 1985 than in 1995. The left side of the 1995 curve is artificially low since ingrowth is not included.

The procedures were applied to all species and species groups, and the results summarized by stand growth components and species groups (Fig. 4). The first column shows that, for all species combined, net growth is 3.9 m^3/ha.yr and mortality is 2.0 m^3/ha.yr, for a gross growth of 5.9 m^3/ha.yr. Most of the net growth is in the conifers (3.3 m^3/ha.yr, col. 2), particularly the white pine (2.1 m^3/ha.yr), while most of the mortality is in the hardwoods (1.6 m^3/ha.yr), 50% of which is in aspen/poplar.

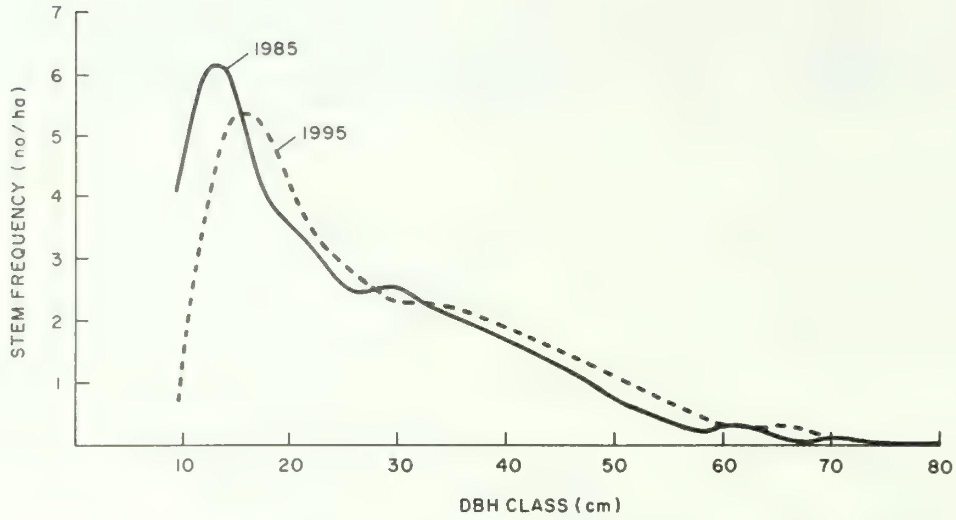

Figure 3. Frequency distribution, 1985 and 1995, White Pine

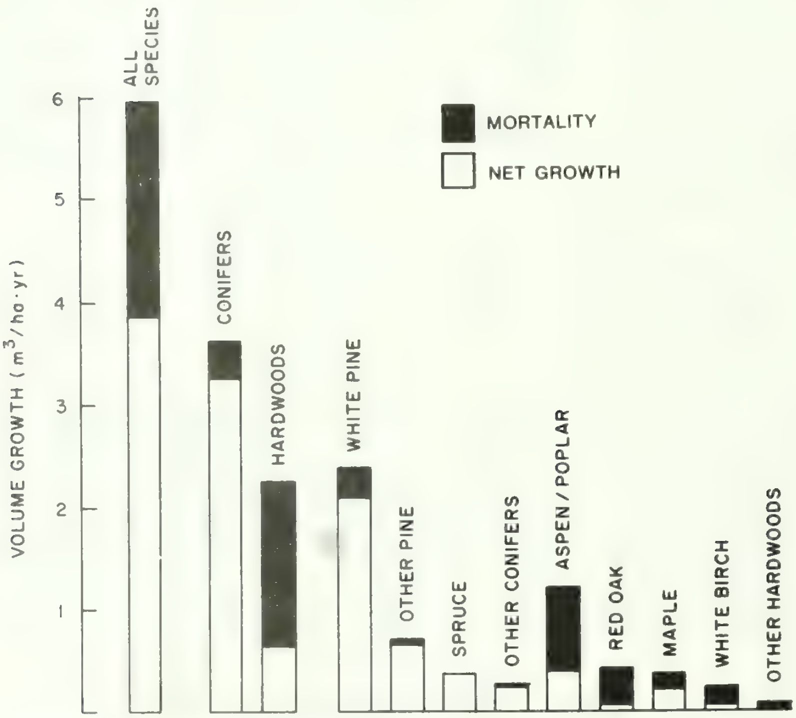

Figure 4. Volume growth by stand components and species groups, 1985-95

DISCUSSION AND CONCLUSIONS

The approach to stem diameter distribution predictions used in this study makes sense at the intuitive level: growth rates of adjacent diameter classes can be expected to be similar. Abrupt changes are unlikely to

reflect "real life"; more likely, they are artifacts of sampling, particularly small sample size. By making use of these relationships in the prediction equations, accuracy can be improved at no additional cost. The existence of small sample sizes, and resulting poorly defined observations, is also taken into account by using weighted regressions.

Utilizing the relationship among diameter class probabilities is one way to obtain better estimates. Another relationship which could be used is that among the growth classes, If both are used, a bivariate model would result. Similarly, it might be possible to utilize the relationship among species.

Increasing sample size per class by increasing class width improves the accuracy of the class estimate. This approach, which applies to diameter as well as growth classes, must be balanced against the need to preserve a certain minimum number of classes to define the trends and yield good overall estimates. For given species, model application and sample size, optimum class widths can likely be derived. Combining data for individual species is another possibility for improving the estimates given that the species have similar growth characteristics and that separate estimates are not required.

A third method of improving the accuracy of the estimates is to include additional, easily obtained variables in the equations. One such variable is stand basal area, which would account for variations in stand density (Solomon et al., 1986).

The sensitivity of the estimates to errors varies considerably. For example, if the predicted number of white pines in diameter class 40 cm and growth class 2 is in error by one tree, the effect is an error of 0.15 m^3, the growth of that tree over the specified period. On the other hand, if the "growth class" is M = mortality, the effect is a much larger error of 1.3/m^3, the total volume of the tree. In the present kind of modelling, events such as mortality are rare, few sets of observations are available and they are not well defined. As a result, prediction equations may be poorly defined and may change significantly as various models are tried, particularly in the presence of constraints. Such changes are often accompanied by significant changes in stand component growth estimates. The conclusion is that particular attention should be paid to the generation of accurate mortality estimates. Another rare event - with associated data deficiencies and modelling inaccuracies - is the growth of large-diameter trees. The approach taken here to use a constant probability, is a technically simple interim solution. A better approach might be to use splined equations, with one equation asymptotic to the X-axis.

As previously noted, ingrowth is not included in this study. As indicated by Bonnor and Magnussen (1986), this exclusion has had no significant effect on volume predictions, while stem frequencies are adversely affected. Over longer periods, volume predictions will of course also be affected.

Therefore, ingrowth must be part of a complete projection system. Other researchers (Buongiorno and Michie (1980), Solomon et al. (1986)) have found ingrowth difficult to predict.

In conclusion, the concept of using growth probability equations to predict stand growth by stem diameter distributions is in the developmental stage. Considerable additional work is required to improve the methodology. At the same time, it appears to yield good results, it makes sense biologically, and it affords an opportunity to analyse and quantify the growth process.

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MODELLING MIXED SPECIES STANDS
WITH SCHEFFE'S CANONICAL POLYNOMIALS

Kadiroo Jayaraman and Robert L. Bailey[1]

ABSTRACT. Stand models for mixed species stands based on static yield functions, transition matrices and difference equations are not satisfactory in many instances. Quite often they do not adequately incorporate information on species composition. A new model form is proposed which relates the increment in biomass or growing stock to present species composition. Proportions of the growing stock in the various species are incorporated into a regression-type model as predictors with the use of a class of Scheffe's canonical polynomials. Since the species composition can exist under different stocking levels, the initial stocking levels become process variables (Cornell 1981). Stand top height can be used as a self-calibrating variable to account for productivity variations in different stands.

INTRODUCTION

Management of uneven-aged mixed forests have gained importance in the recent past due to a number of reasons, the prominent one being the increased public concern and involvement in forest management decision making. Attempts on modelling the growth of such forests have been few in the past and satisfactory simulators are lacking in many cases. The present work is an attempt in this direction.

A mixed forest in the context of this work implies any forest in which the individual stands that compose the basic mensurational unit contain a mixture of species. Typically a mixed forest will have an uneven-aged structure. The different species may be ecologically quite similar or composed of several ecological groups with each group tending to be dominant in a particular stratum of the canopy or on particular microsites or in different successional phases following gap formation or harvesting operation (Alder, 1980).

A review of literature is completely avoided here for lack of space except to mention that many of the models for mixed stands have been found based on static yield functions, transition matrices and

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differential equations. It has been found that the problem of species composition has not been effectively tackled in these models.

A NEW MODEL FOR MIXED STANDS

A distance independent whole stand growth model which is directly adaptable to simulation works is proposed in the following.

Let there be an uneven-aged mixed stand having q components, with respect to the species, growing in a uniform site. The proportions of the total growing stock occupied by the q components are denoted by x_1, $x_2, \ldots, x_q$. The model in its simplest form is

$$I_i = f\,(\underline{x}')\ ;\ i = 1, \ldots, q \qquad (1)$$

where I_i is the increment w.r.t. a measurable characteristic for the ith species.

$$\underline{x}' = (x_1, x_2, \ldots, x_q) \quad \text{and} \quad \sum_{i=1}^{q} x_i = 1$$

An error term is supposed to be included in eq. 1 and all such equations following. This is omitted for the sake of convenience in presentation. Moreover $f(\cdot)$ represents a general functional form rather than any specific one.

The set of equations in (1) is constrained by $\hat{I} = \sum_{i=1}^{q} \hat{I}_i > 0$ where $\hat{I}$ represents the total predicted increment from $I = f\,(\underline{x}')$.

To account for the uneven-aged structure, the vector $\underline{x}$ may be expanded by the diameter class proportions for each species as follows:

$$\underline{x}'\ (\text{uneven}) = (x_{11}, x_{12}, \ldots, x_{1r}, \ldots x_{q1}, x_{q2}, \ldots, x_{qr}) \qquad (2)$$

where x_{ij} indicates the proportion of the total growing stock occupied by the ith species in the jth diameter class.

The eq. (1) is found to belong to the class of mixture models expounded by Cornell (1981). For instance, consider an mth degree polynomial in x_i

$$\eta = \beta_0 + \sum_{i=1}^{q} \beta_i\, x_i + \sum_{i \le j}^{q}\sum^{q} \beta_{ij}\, x_i\, x_j + \sum_{i \le j \le k}^{q}\sum^{q}\sum^{q} \beta_{ijk}\, x_i\, x_j\, x_k + \ldots \qquad (3)$$

The parameters β_i, β_{ij}, β_{ijk} associated with the terms are not unique because of the constraint

$$\sum_{i=1}^{q} x_i = 1$$

An alternate to eq. (3) is derived by multiplying some of the terms by the identity $(x_1 + x_2 + \ldots + x_q) = 1$ and simplifying. The resulting equation has been called the canonical polynomial or simply the {q, m} polynomial.

For example, with m = 1

$$\eta = \beta_0 + \sum_{i=1}^{q} \beta_i x_i \tag{4}$$

and upon multiplying the β_0 term by $(x_1 + x_2 + \ldots + x_q) = 1$ the resulting equation is

$$\eta = \beta_0 \left(\sum_{i=1}^{q} x_i\right) + \sum_{i=1}^{q} \beta_i x_i = \sum_{i=1}^{q} \beta_i^* x_i \tag{5}$$

where $\beta_i^* = \beta_0 + \beta_i$ for all i.

Similarly the general second degree polynominal in q variables can be transformed to

$$\eta = \Sigma \beta_i^* x_i + \sum_{i<j}\Sigma \beta_{ij}^* x_i x_j \tag{6}$$

where $\beta_i^* = (\beta_0 + \beta_i + \beta_{ii})$ and $\beta_{ij}^* = \beta_{ij} - \beta_{ii} - \beta_{jj}$ i, j=1, ... q, i < j.

The terms $\beta_i^* x_i$ and $\beta_{ij}^* x_i x_j$ in {q,1} and {q,2} polynomial equations have simple interpretations. The parameter β_i^* represents the expected response to pure component i and pictorially β_i^* is the height of surface above the simplex at the vertex where $x_i = 1$ for i = 1, 2, ..., q. β_{ij}^* represents the interaction among the components and could indicate synergistic or antagonistic effects depending on the sign.

Eq. (1) essentially tries to explain growth in terms of species composition. But variables like stocking, site quality and age structure could influence the growth and accordingly their effects are to be incorporated. In the parlance of mixture models they are called process variables. The process variables are not linear functions of the mixture components and will be denoted by Z_j.

In line with Cornell (1981) the equation (1) is modified to

$$I_i = f\,(Z_j, \underline{x}') \tag{7}$$

In particular if the initial stocking in basal area of all species (B) is considered a process variable and no species interaction is envisaged, eq. (7) may take the form

$$I_i = \sum_{i=1}^{q} [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m] x_i \tag{8}$$

where the part of the function relating to the process variable now correspond to the growth rate equation of the Richard's function. The above discussion may suggest the following equation as well which is an extension of the Richard's function to the case of multiple species

$$I = \sum_{i=1}^{q} \gamma_i^{(1)} Bx_i + \sum_{i=1}^{q} \gamma_i^{(2)} (Bx_i)^m + \sum_{i<j}\sum \theta_{ij}^{(1)} B^2 x_i x_j + \sum_{i<j}\sum \theta_{ij}^{(2)} B^{2m} (x_i x_j)^m \tag{9}$$

where $I = \sum_{i=1}^{q} I_i$

The first two terms on the R.H.S. indicate the sum of catabolic and anabolic rates and the last two terms represent interaction among anabolic and catabolic rates respectively.

When uniformity of the site cannot be assumed a method to discriminate the productivity levels will have to be evolved. In the case of even-aged stands, the development of site index equations proceeds by establishing a height/age relationship followed by a prediction equation of the form

$$S = f\,(H, A, A_0) \tag{10}$$

where S = site index (i.e., the height attained at a reference age A_0), and H = average or top height of the stand at age A.

In an uneven-aged mixed stand under natural regeneration, the stand age (A) is not defined and therefore a proxy to age has to be found. In the case of undisturbed stands, it can be safely assumed that the basal area (B) is a function of age, i.e.,

$$B = \phi(A) \tag{11}$$

where ϕ need not be linear. Now, if we can find $\Psi(B)$ such that $\Psi(B)$ is proportional to A, then $\Psi(B)$ qualifies as a proxy to age. For instance take the simple example wherein we have

$$\ln B = \beta A^{-1} \tag{12}$$

$$(\ln B)^{-1} = A\beta^{-1} \tag{13}$$

and thus $(\ln B)^{-1}$ is a proxy to age.

Now a site index system similar to (10) can be tried in the present case like

$$S = f\,(H, \Psi(B), \Psi(B_0)) \tag{14}$$

where H, the top height is allowed to cover the dominants and codominants in an extended scale to take account of the mixed nature of the stands. (Extended to mean a larger portion of the population. This will include more species than the few isolated that are very tall). In particular, consider the following height/age relation under an anamorphic system of site index curves

$$H_i = k_{0i}\, e^{\beta_1 A^{-1}} \tag{15}$$

Substitution of $(\ln B)^{-1}$ for A in (15) gives the following equations.

$$\ln H = \beta_0 + \beta_1 \ln B \tag{16}$$

$$\ln S = \ln H - \hat{\beta}_1 \ln \left(\frac{B}{B_0}\right) \tag{17}$$

where S is the site index at $B = B_0$.

When species composition is included in predicting the site index the following equations may result

$$\ln H = \gamma_0 + \sum_{i=1}^{q} [\gamma_i \ln B]\, x_i \tag{18}$$

$$\ln S = \ln H - \sum_{i=1}^{q} [\hat{\gamma}_i \ln B] x_i + \sum_{i=1}^{q} [\hat{\gamma}_i \ln B_0]\, x_{i0} \tag{19}$$

where x_{i0} , i=1, ..., q indicates a reference species composition.

Inclusion of process variables like site index may call for additional equations of the form

$$S_{t+1} = f\,(S_t) \tag{20}$$

for the purpose of simulation.

MODEL VALIDATION

Results of some preliminary investigations with the above model are reported herein. The results are in no way complete and further works are in progress. These are presented to serve as guidelines in analysis.

The data were obtained from permanent sample plots maintained by a large forest products company in Southwestern Georgia. The measurements were spread over the past twenty-five years at five-year intervals. The one hundred and thirty plots in which no cutting was done were used in our analysis. The plot size was 0.0578 ha. The species were grouped into 5 broad classes: (1) pines, (2) oaks, (3) soft hardwoods, (4) hard

hardwoods and (5) miscellaneous and understory species. The species composition (x_i's) was expressed in terms of basal area.

The following equation was fitted through nonlinear least squares.

$$I_i = [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m] x_i + [\gamma_{(-i)}^{(1)} B + \gamma_{(-i)}^{(2)} B^m] x_{(-i)}$$

$$+ [\Theta_{i(-i)}^{(1)} B + \Theta_{i(-i)}^{(2)} B^m] x_i x_{(-i)} + \varepsilon \qquad i = 1, \ldots, q \tag{21}$$

where I_i is the mean annual increment in the basal area over five-year period for the ith species.

$x_{(-i)} = 1 - x_i$

B = total basal area of the stand.

The Adj R^2's are reported in Table 1.

Top height for each plot was computed as the mean height of the tallest twenty-five percent of the trees in the stand and eq. (18) was fitted which gave an Adj R^2 of 0.4017. It is intended to calibrate the residual variation of this fitted equation through site index. Site index was computed through eq. (19) and formed the additional variable in the following set of equations. The x_{io}'s were fixed at the mean species composition over all the plots and B_0 at 30 m²/ha.

$$I_i = [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m + \gamma_i^{(3)} S]x_i + [\gamma_{(-i)}^{(1)} B + \gamma_{(-i)}^{(2)} B^m + \gamma_{(-i)}^{(3)} S]x_{(-i)}$$

$$+ [\Theta_{i(-i)}^{(1)} B + \Theta_{i(-i)}^{(2)} B^m + \Theta_{i(-i)}^{(3)} S] x_i x_{(-i)} + \varepsilon \qquad i=1, \ldots, q \tag{22}$$

The results are given in Table 1. There seems to be partial improvement in the R^2 values by adding a linear term of site index.

The variability in the age/size of trees could also influence the growth process and accordingly a linear term involving the coefficient of variation (C) of tree basal area was also included in eq. 22. The results are available in Table 1. The overall variability in the stand seems to have little influence on the increments after that accounted by the species composition and site index.

TABLE 1. Adj R^2 values for the fitted models (Adj R^2 = 1 - [error mean square]/[total mean square]).

Groups	Dependent variable	Process variables involved		
		(B, B^m)	(B, B^m, S)	(B, B^m, S, C)
		...............Adj R^2.................		
Pines	I_1	0.6174	0.6860	0.7033
Misc & Understory spp.	I_2	0.9093	0.9290	0.9350
Oaks	I_3	0.4904	0.4880	0.5139
Soft hardwoods	I_4	0.4733	0.4906	0.4852
Hard hardwoods	I_5	0.7059	0.8020	0.8395
Total	I	0.2332	0.2889	0.3285

If $\Sigma \hat{I}_i$ happens to be negative, one of the equations in (7) may be replaced by

$$I = f\,(B, S, C, \underline{x}') \tag{23}$$

where $I = \sum_{i=1}^{q} I_i$

Since eq. (23) involves a large number of terms, model reduction techniques are to be used. It may be noted that for the process variable part, i.e., $I = f(B, S, C)$, different combinations of these variables involving crossproduct and higher order terms can be considered. A stepwise regression could be carried out before the aspect of species composition is included in the model. As for the mixture related variables (x_i) Cornell (1981) gives some screening procedures based on the effects (E_i) of each x_i on the dependent variable. Starting with a planar model like

$I = \sum_{i=1}^{q} \beta_i x_i$, the E_i's are defined as

$$E_i = R_i [b_i - \frac{1}{(q-1)} \sum_{j \neq i}^{q} b_j] \tag{24}$$

where R_i = range of x_i, $b_i = \hat{\beta}_i$

Components having similar effects could be merged thereby reducing the number of components. In the present case calculations showed that the

components x_3, x_4 and x_5 could be combined and also the resulting groups do not interact. Thus the following equations were fitted.

$$I = \sum_{i=1}^{3} [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m] x_i \tag{25}$$

where $x_3 = 1 - (x_1 + x_2)$

$$I = \sum_{i=1}^{3} [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m + \gamma_i^{(3)} S] x_i \tag{26}$$

$$I = \sum_{i=1}^{3} [\gamma_i^{(1)} B + \gamma_i^{(2)} B^m + \gamma_i^{(3)} S + \gamma_i^{(4)} C] x_i \tag{27}$$

The results are reported in Table 1. It seems harder to predict the total increment rather than the increment in the individual components.

Some of the low values for Adj. R^2 in Table 1 are suspected to be due to considering the net increment as the dependent variable which included the ingrowth. The net increments were arrived at as follows

$$I = IN + SR - MR \tag{28}$$

IN = Ingrowth
SR = Survivor growth
MR = Mortality

In fact the ingrowth and survivor growth are supposed to be responding in opposite directions to the initial stocking and would have disturbed the strength of the relations considered here. In future trials growth components rather than net growth are suggested for dependent variables.

Finally, a first order difference equation was fitted between successive site indices as

$$S_t = \alpha + \beta S_{t-1} + \varepsilon \tag{29}$$

with an Adj. R^2 value of 0.7830.

More detailed results will be published shortly.

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GROWTH PROJECTION IN MIXED DIPTEROCARP FORESTS IN SOUTHEAST ASIA

Guillermo A. Mendoza and Roberto B. Rapera

ABSTRACT. Growth projection for mixed dipterocarp forests in Southeast Asia is still in its early developmental stage. To date, most of the research works on growth and yield modelling are pioneering efforts based primarily on methods developed in the U.S. and Europe.

This paper provides an overview and a synthesis of the approaches and results of some forest growth modelling studies within the region, particularly for the dipterocarp forest; the most dominant and economically significant forest in the region. Moreover, the paper also examines existing growth and yield models and suggests some strategies and recommendations to improve them. Emphasis is given to growth projection and development of logged-over, uneven-aged and mixed dipterocarp forests. Results from some studies in the Philippines and Indonesia are described.

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INTRODUCTION

The mixed Dipterocarp Forests of Southeast Asia extend from Southern Thailand through Sumatra, West Malaysia, Borneo and to the Philippines. They form the main vegetative type on the western portion of the Indo-Malayan Rain Forest block. Because they contain species of high commercial values, they have been exploited heavily since about 1960 and have contributed significantly to the development of the economics of the Southeast Asian region.

Current Cutting Systems

Since the primary focus of this paper is growth and yield prediction on mixed, cut-over uneven-aged dipterocarp forests, a brief desription of the harvesting systems within the region is described in this section.

There are at least two major cutting systems that have evolved in the region, namely: The Philippine and the Indonesian Selective Logging Systems. Both systems rely heavily on the yield of the residual stands.

The Philippine Selective Logging System is both a silvicultural and a harvesting system. As a silvicultural system, it requires the following treatments: 1) tree marking to identify both the trees to be cut and those that are to be left as residuals, 2) residual inventory to evaluate the status of the logged-over forest and the residual trees, and 3) timber stand improvement. As a harvesting system, it specifies the type and number of trees to be harvested (based on diameter size), as well as the number of residual trees. The cutting cycle ranges from 30 - 45 years depending on climatic (or geographical) region.

The Indonesian Selective Logging System is also a diameter-based selection cutting system. The diameter limit of trees to be cut is 50 cms, while the cutting cycle is 35 years for commercially valuable trees like the dipterocarps. The system also requires at least 25 trees with diameter 35 cm or bigger to be marked as residuals. Enrichment planting is required mainly in open areas caused by cableways, tractor maneuvers, and log yards. Timber stand improvement must be conducted to improve the condition of the stand and the survival of the residual trees.

GROWTH AND YIELD STUDIES

PHILIPPINES

Early growth studies on the Philippine dipterocarp (mixed) rainforests were made in 1920. The final results of these studies were expressed in simple growth percent of the growing stock which ranged from 1.38 to 1.91 percent. In

1954, in connection with the formulation of the Selective Logging System as the management system to put the Philippine dipterocarp forests under initial regulation, another growth study was started in selectively logged dipterocarp forests in southern Philippines. This was followed by the establishment of permanent growth plots throughout the cut-over forests of the country. As of today, there are some 3,000 such growth plots.

Results of analysis of growth data from the first subsets of these plots were reported by Reyes (1968). The diameter at breast height (DBH) periodic annual increment (PAI) of the commercial tree species were determined from free-hand curve values. Growth projections were made based on estimates of the number of years for a tree to stay in a DBH class, the "age" of a tree when it reaches a DBH class, and the DBH reached after so many years form an initial DBH class.

Chinte (1970) analyzed the growth of logged-over mixed species groups from 63 growth plots within the timber concession a company located in southern Philippines. From this study, the average periodic annual diameter growth of the different species groups were estimated.

In 1975, two similar studies were conducted for two companies located in southern Philippines. One study was done by Revilla, et. al. (1976) at the initiative of the company's management, and the second study by Canonizado (1976). One hundred forty eight measurements from 51 plots and 242 measurements from 50 growth plots were used for both studies, respectively. There were at least two measurements of the growth plots used in these studies; and the data covered as much as 20 years after logging.

In these studies, the authors wanted to develop yield prediction functions which include the major factors affecting stand growth/yield, notably: time, stand density and site quality; something that has not been done before in the tropical mixed uneven-aged forests. Their biggest problem was the absence of a ready measure of site quality in the Philippine dipterocarp forests. The use of site index was not possible because of the inability to determine the age of trees in the natural stands. Four alternative ways were considered and after a thorough analysis, the mean total height (MTH) of the biggest residual trees (i.e. 60 to 70-cm. DBH in the case of the first study and 60 to 80 cm DBH in the case of the second study) were found to be significant explanatory variables in the merchantable height equations for the different species groups and in the stand yield equations in both studies. As such, MTH was considered an acceptable indicator/measure of site quality for the purposes of these two studies.

Growth and Yield Equations

For the first study (Revilla et al, 1976), the following yield equations were derived;

$$\log YLDT = 0.7416 + 7775 \log BO + 0.3952 \log (YEAL + 1)$$

$$+ 0.008105*S)(YEAL +1) + 0.1589 \log BO \log S$$

$$R = 0.88;\ MSE = 0.007225;\ n= 148$$

where: YLDT is the total yield from 15 cm DBH and bigger trees from all species; BO is the initial stand density in sq m/ha; S is the site quality indicator (i.e. siticator) in meters; and YEAL is the number of years elapsed after logging.

This equation is valid statistically and satisfies adequately the desirable criteria of a yield prediction function.

To obtain some insights on the development of the dipterocarp component of the stand, an independent yield prediction equation for the dipterocarps (primarily Philippine mahogany and apitong [Dipterocarpus] species) based on BPO (dipterocarp basal area at YEAL = 0), YEAL, and siticator was derived. The prediction equation is as follows:

$$\log YLDP = 0.8429 + 0.4046 \log BPO + 0.3367 \log (YEAL + 1)$$

$$+ 0.4629 \log BPO \log S$$

$$R = 0.95;\ MSE = 0.03648;\ n = 153$$

In the second study conducted for another company in southern Philippines (Canonizado, 1976), the final equation adopted is as follows:

$$\log Y = 2.6469 + 1.5696 \log B_1 \log S - 0.0256 (t + 15)*$$

$$\log B_1 - 1.4015 \log S + 0.0352 B_1^2/(t + 15)^2$$

$$- 0.0211 (t + 15)$$

where Y is net volume yield of dipterocarp trees in cu m/ha; B_1 is basal area of dipterocarp spp. at plot establishment in sq m/ha; S is the siticator or mean total height of Philippine mahogany spp (57.6 - 92.5 cm in DBH) in meters; t is time elapsed in years from the base measurement.

Mendoza and Gumpal (1987) developed a growth projection model for a selectively cost-over dipterocarp forest in northern Philippines.

In developing the model, different variations of the general functional relationship between stand yield as a dependent variable and initial basal area, site quality and time as explanatory variables were tested. The final form of the functional relationship is a linear model involving the logarithm of stand yield as a function of the logarithm of the initial basal area and time, and the ratio of site quality and time. A set of abstracted time series data from sample plots based on actual logging settings was used. Time was expressed in terms of the number of years elapsed after logging operations. A site quality indicator for the selectively cut-over dipterocarp forest was developed using the average total height of the dominant and codominant dipterocarp trees which were left after logging. The final yiel equation is;

$$\log YLD = 1.337 + 0.39*\log (B_o) + 0.34*\log T + 0.002*(S/T)$$

where: YLD is the yield of dipterocarp trees 15 centimeters and bigger in diameter; B_o is the initial stand basal area of dipterocarp trees 15 centimeters and larger in diameter based on the residual inventory after logging (in sq m/ha); T is the time elapsed or number years after logging; S is site quality indicator or mean total height of dipterocarp trees 50 to 80 centimeters in diameter (in meters).

Growth Simulation for the Philippine Dipterocarp Forests

Revilla (1978) developed a stand growth simulator (GYSIM) primarily to evaluate the Philippine Selective Logging System and other timber management strategies. This is the first comprehensive growth simulation model for logged-over dipterocarp forests in Southeast Asia.

GYSIM is a simple probalistic model. It looks at individual trees in the stand, determines by means of a mortality function and a random number generator whether or not a tree survives the growing period, and grows the survivor tree into the next period or generates a number of established reproduction based on the size of the tree that dies. A survivor tree is grown into the next period by a DBH growth equation with DBH and stand basal area or stand treatment, DBH, and YEAL as explanatory variables. Periodic ingrowth is based on the number of established reproduction after logging and those which take the place of trees that die at various points in time.

INDONESIA

One of the concerns in implementing the harvesting guidelines of the Indonesian Selective Logging System as formulated in 1972, is its capability to sustain future harvests. In addressing this issue, Mendoza and Setyarso (1986) developed a transition matrix forest growth model to

evaluate the harvesting guidelines of the Selective Logging System and other alternative harvesting schemes in Indonesia. The model developed is an adaptation of the model described by Buongiorno and Michie (1980).

The transition matrix growth model G is expressed as;

$$
\begin{array}{cc}
\text{Diameter classes} & \begin{array}{ccccccc} 1 & 2 & 3 & \ldots & i & \ldots & n \end{array} \\
\begin{array}{c} 1 \\ 2 \\ \\ i \\ \\ n \end{array} &
\begin{bmatrix}
 & a_1 & & & & & \\
 & b_2 & a_2 & & & & \\
 & & & & & & \\
 & & & & b_i & a_i & \\
 & & & & & & \\
 & & & & & b_n & a_n
\end{bmatrix}
\end{array}
$$

where b_i is the probability that a tree belonging to diameter class i will remain in the same diameter class after the growth period; and a_i is the probability that a tree belonging to diameter class i will move to the next higher diameter class after the growth period.

Given the growth transition matrix G, the form of the growth projection model is;

$$Y_{(t+\tilde{o})} = G(Y_t) + C$$

where $Y_{t+\tilde{o}}$ is a vector representing the projected diameter distribution after the growth period $\tilde{o}$; Y_t is the diameter distribution at time t; C is the constant ingrowth. Hence, given an initial condition of the stand Y_o, the projected diameter distribution after k growth periods, each of length $\tilde{o}$ can be estimated by the functional relationship;

$$Y_{k\tilde{o}} = G^k(Y_0) + \sum_{i=0}^{k-1} G^i C$$

In examining the Indonesian Selective Logging System relative to the sustainability issue, a case study involving a forest concession located in East Kalimantan was used. A comparison was made between the projected stand structure at the end of 35 years, and the initial structure prior to the first harvest. Results show that there is no significant difference between these two stand structures. Hence, it can be observed that the system can support the second harvest. However, analysis of the third cutting cycle (i.e. after the second harvest) show that if an equal volume of harvest (i.e. the same as the first period harvest) must be removed during the second harvest, the required growing stock at the start of the second period is twice as much as the amount prescribed by the selective logging system. Hence, it is apparent that the volume of harvest cannot be

sustained after the second cutting cycle, if the residual growing stock prescribed by selective logging system is implemented.

Alternative Harvesting Schemes

The preceeding discussions and evaluations suggest that the system may not be able to sustain future harvests on a longer term. Hence, for the company considered in the case study, adjustments must be made on the volume of harvest during the second and succeeding cutting cycles in order to provide sufficient growing stock for future harvests.

Harvest scheduling problems involving constraints such as sustainability and volume of harvest can be analyzed using mathematical programming techniques. Mendoza and Setyarso (1986) developed a linear programming model to determine the number of trees to be cut in each harvest, and the associated diameter distribution of the residual growing stock. Relative to the Indonesian Selective Logging System, the model developed is intended to determine the minimum residual growing stock that can sustain a given volume of future harvests. The mathematical model for optimizing the residual stand structure is formulated as follows:

$$\text{Minimize } Z = 1'(Y_0 - h) \tag{1}$$

$$\text{subject to: } (I - G)Y_0 + G^k h \le \sum_{i=1}^{k-1} G^i C \tag{2}$$

$$V_{min} \le vh \le V_{max} \tag{3}$$

$$h \le Y_0; \tag{4}$$

$$Y_0, h \ge 0$$

where: h is the harvest vector which denotes the number of trees cut in each diameter class; v is the vector representing the volume of cut in each diameter class; and V_{min}, V_{max} are minimum and maximum volume constraints, respectively.

The formulation in (1) - (4) allows for the evaluation of various harvesting schemes. For instance, the diameter limit of 50 centimeters required by the system can be modelled by expressing the harvesting vector h as:

$$h' = [0, 0, \ldots, h_{50-55}, h_{55-60}, h_{60-65}, \ldots, h_{>70}] \tag{5}$$

Other diameter limits may be evaluated and optimized by formulating the harvest vector h in the same manner as in equation (5). The length of the cutting cycle may also be analyzed by looking at various time periods expressed as multiples of the growth period Õ.

CONCLUSIONS

Growth projection for mixed dipterocarp forests in Southeast Asia is still in its early developmental stage. In general, existing growth models in tropical mixed forests within the region, particularly for logged-over dipterocarp forests lack comprehensiveness and depth. For instance, an adequate measure for site quality and its effect in growth projection has not been sufficiently studied. Moreover, current models within the region are, in general, static and lack the capability to assess the effects of alternative management regimes with various intensities.

Although these models appear to be inadequate, they are nevertheless useful at least for the purpose they were intended for. Refinements can still be made to make them more dynamic and accurate as the need for more precise estimates become more important within the region.

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A GROWTH AND YIELD MODEL (FIBER) FOR MULTIPLE SPECIES STANDS WITHIN DIFFERENT FOREST TYPES

Dale S. Solomon and Richard A. Hosmer[1]

ABSTRACT. Predicting growth and yields for spruce-fir, northern hardwood, and associated forest types of different species mixtures can be accomplished with a two-stage matrix model, FIBER. Changes in stand growth of multiple species composition are presented as ingrowth, probability of survivor growth, and probability of mortality. These annual transition probabilities are expressed as functions of tree size, basal area, and species composition. The model uses diameter distributions of classes ranging from 12.7 to 76.2 centimeters for each of the commercial species in these forest types. Thinning and harvest yields are obtainable for managed and unmanaged stands, both even-aged and multi-aged, over a range of densities, site indices, and intermediate treatments. The model is evaluated using independent data sets for different species compositions, densities, silvicultural treatments, and harvesting practices across forest stands within a region of different forest types. FIBER is user friendly, written in Fortran 77, and is available for IBM compatible microcomputers.

INTRODUCTION

In northern New England, United States, and the Maritime Provinces, Canada, spruce-fir and northern hardwood are the major forest types. The many different species result in different stand compositions of predominately hardwoods, softwoods, or mixed species from both types. To predict the growth response of these forest stands, a modeling framework was developed to include the interaction of different species on the growth of stands with different levels of density, silvicultural treatments, and management practices (Solomon et al. 1986).

The initial development of the model, FIBER, was based on the growth of stands without catastrophic stress from the environment such as insect attacks, diseases, drought, and so on. By combining data from growth studies, more than 3,000 remeasured plots from Nova Scotia, New Brunswick, Maine, New Hampshire, Vermont, and northern New York were used to further develop the model FIBER (Figure 1). These growth plots were measured in 5-year intervals at various times between 1950 and 1980 and were from both managed and unmanaged stands covering a wide range in species compositions, sites, management options, and densities (Solomon et al. 1987). The model is being modified and tested to include the regional extent of the spruce-fir, northern hardwood, and associated types in the northeast. Further expansion will provide a basis for testing spatial and temporal differences required within the forest response program of the National Acid Precipitation Assessment Program.

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Figure 1. Dotted area is geographic region of growth plot data used for model construction and modification.

MODEL DEVELOPMENT

FIBER is a two-stage matrix model that uses transition probabilities of trees remaining in the same diameter class, increasing to a larger diameter class, or dying from one inventory to the next. One stage of the model is to predict the transition probabilities using stand parameters of stand density, tree size, and proportion of hardwoods. The other stage is to incorporate these probabilities into growth matrices (G_t) that are used to project a diameter distribution over time in 5-year intervals (Solomon et al. 1986).

The initial input for the model is a species specific diameter distribution that can be given as a vector $\underset{\sim}{y}$, where y_{it} is the number of trees in diameter class i at time t. The trees within each diameter class can survive and stay in the class (with probability a_{it}); survive and grow one diameter class larger (b_{it}); survive and grow two diameter classes larger (c_{it}); or die (m_{it}). Trees are assumed not to grow three diameter classes in a 5-year period. By combining each of these probabilities with the vector of the number of trees in each diameter class and including the ingrowth (I) that grew into the 12.7-cm class by time t+5, the model can be written in matrix form:

$$\begin{bmatrix} y_{5,t+5} \\ y_{6,t+5} \\ \cdot \\ \cdot \\ y_{30,t+5} \end{bmatrix} = \begin{bmatrix} a_{5,t} & 0 & 0 & \cdot & \cdot & \cdot & 0 \\ b_{5,t} & a_{6,t} & 0 & & & & 0 \\ c_{5,t} & b_{6,t} & a_{7,t} & & & & \cdot \\ \cdot & \cdot & \cdot & & & & \cdot \\ 0 & \cdot & \cdot & & c_{28,t} & b_{29,t} & a_{30,t} \end{bmatrix} \begin{bmatrix} y_{5,t} \\ y_{6,t} \\ \cdot \\ \cdot \\ y_{30,t} \end{bmatrix} + \begin{bmatrix} I \\ 0 \\ \cdot \\ \cdot \\ 0 \end{bmatrix}$$

Mortality (m_{it}) appears implicitly in the model since the matrix is a survivor matrix with $m_{it} = 1.0 - a_{it} - b_{it} - c_{it}$.

The mortality and growth rate of different species are altered as the species composition and density change before and after thinning (Solomon 1977, Solomon and Frank 1983). To provide a flexible model that can reflect different growth rates, the a, b, c, and m probabilities were each expressed as functions of initial basal area, residual basal area after thinning, size of diameter class, and the proportion of hardwoods (Solomon et al. 1986; Solomon et al. 1987).

Ingrowth into the beginning diameter class was estimated from regression equations. After testing numerous variables, the best relationship with ingrowth was residual basal area, the proportion of hardwoods, and the percentage of the species in the stand (percent basal area).

The data sets used did not have site index recorded for all plots, therefore, site was not included as a variable in the prediction of the transition probabilities. However, softwood stands were considered to have average site indices of 40 to 50 for red spruce at base age 50, and hardwood stands had site indices of 50 to 60 for sugar maple at base age 50. To model the changes in growth rate due to site, the b and c values were modified proportionately using a base of site index 50 for softwood stands, 60 for hardwood stands, and 55 for mixed species stands.

MODEL RELIABILITY

Spruce-fir and mixed species (0.08-ha plot) data from the Penobscot Experimental Forest, Bradley, ME, were used to test FIBER for different management schemes: an unregulated harvest system (20 plots), a selection system (21 plots), and a diameter limit system (13 plots) (Figure 2). All plots were harvested initially and then remeasured at 5-year intervals for 25 years. The selection system had intermediate thinnings at years 10 and 20, and the diameter limit harvest had one additional thinning at 20 years. The unregulated harvest did not have any intermediate thinnings.

The model accurately predicts the total volume (m^3/ha) for these three different management schemes within 10 percent or less difference. Field measurements were not taken at exactly 5-year intervals, therefore the predicted value does not consistently match the actual value each year. FIBER is currently being modified to allow for estimates of less than 5 years using a method developed by Harrison and Michie (1985).

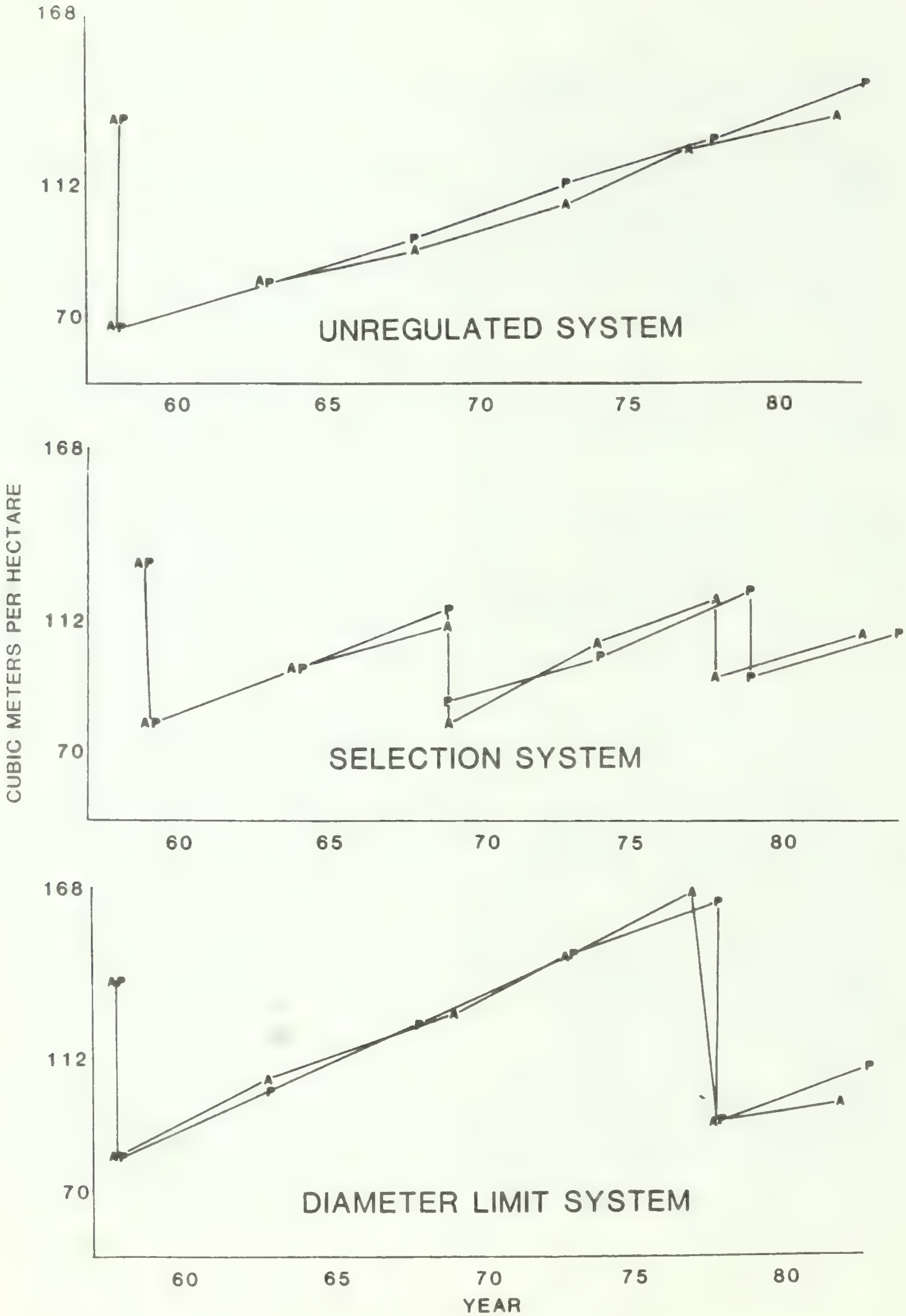

Figure 2. Comparison of 25 year average actual (A) and predicted (P) volumes (m^3/ha) for the unregulated system, selection system, and diameter limit system of management.

Table 1. Actual and predicted 10-year average stand volume (m^3/ha) for softwood, hardwood, and mixed species forests using Forest Service survey re-measured plots in Maine.

Method	Species[a/]														
	BF	Sp	He	Ce	OS	SM	RM	YB	PB	Be	WA	As	OH	Total	% diff
							Softwood (n=339)								
Actual	31.9	38.6	7.3	23.7	17.6	0.8	7.0	1.9	3.5	0.2	0.2	1.6	1.0	135.5	-0.9%
Predict	33.0	39.1	7.4	23.4	14.9	0.8	7.2	2.2	3.6	0.3	0.3	0.9	1.0	134.3	
							Hardwood (n=168)								
Actual	3.4	3.2	1.9	0.5	0.8	20.4	19.1	10.1	5.8	20.3	2.7	8.0	7.0	103.1	0.3%
Predict	4.0	3.0	2.0	0.5	0.6	21.1	19.8	10.9	6.0	21.6	3.5	5.4	5.1	103.5	
							Mixed Species (n=187)								
Actual	22.0	16.9	8.1	4.8	5.1	8.3	17.9	10.1	8.0	4.8	1.3	5.4	4.0	116.7	-0.1%
Predict	22.3	15.3	8.5	4.8	4.8	8.2	19.2	11.4	8.3	5.7	1.6	3.2	3.3	116.6	

a/ BF = balsam fir (Abies balsamea (L.) Mill.); Sp = spruce (Picea spp.); He = eastern hemlock (Tsuga canadensis (L.) Carr.); Ce = northern white cedar (Thuja occidentalis L.); OS = other softwoods (Larix laricina (Du Roi) K. Koch and Pinus strobus L.); SM = sugar maple (Acer saccharum Marsh.); RM = red maple (Acer rubrum L.); YB = yellow birch (Betula alleghaniensis Britton); PB = paper birch (Betula papyrifera Marsh.); Be = American beech (Fagus grandifolia Ehrh.); WA = white ash (Fraxinus americana L.); As = aspen (Populus tremuloides Michx.); OH = other hardwoods (Betula populifolia Marsh., Acer pennsylvanicum L., Prunus pennsylvanica L. F., Fraxinus nigra Marsh.).

For a broad-base regional validation of the model, the growth components from a subset of US forest survey permanent plots from 1960 to 1970 were developed (Ferguson and Kingsley 1972). Plots with more than 20 square feet of basal area and classified as commercial forest land were used for the data set for Maine. The 694 plots were grouped by species composition of softwood (> 65 percent softwood species), hardwood (< 25 percent softwood species), or mixed hardwood-softwood (between 25 to 65 percent softwood species). Beginning with the 1960 data, the model was used to project each plot for 10 years, and the average predicted volumes by species are compared with the average actual volumes in 1970 (Table 1).

The summary of the forest survey of Maine cannot be directly compared because of different number of plots, volume equations, and forest type grouping. However, when the actual volume was compared to the predicted volume from the model FIBER, the results are less than 1 percent difference. The grouping of the plots into forest type by species composition indicates that the model will predict well on a regional basis. Predictions for most of the individual species are close to the actual after 10 years of growth and most of the yields are within 10 percent of the actual. As might be expected, the category of other softwood and other hardwood indicates some differences between actual and predicted because of the different species in the category. Similarly, aspen was also under-predicted possibly because of the data set used in model construction.

APPLICATION

The model's ability to incorporate the interaction of different species compositions on the growth response of the stand as the diameter distribution changes provides a reliable method of predicting forest yields. Predicting the transition probabilities as a stand grows from one diameter distribution at time t to a second diameter distribution at time t+5 can be applied to any representative inventory. The construction and development of the matrix model FIBER has provided forest managers and educators with a tool for reliably predicting the growth and yields of stands and forest types in the Northeast. The model has progressed from a stand model that follows the growth response of intensively managed stands to a model that reliably predicts the growth response of large regional areas with mixed species forest types. The model is being used as the base growth predictor of the commercial spruce-fir forest of the Forest Response Program for the National Acid Precipitation Assessment Program. Modifications are being applied to the transition probabilities as a method of testing for temporal or spatial differences in forest stands. FIBER allows the flexibility of testing for stress on specific species while concluding the growth interaction of other species in the stand.

SOFTWARE

Program Name: FIBER 2.0

Programmer(s): Richard Hosmer

Hardware and Software Requirements:

Computer model	IBM PC or compatible
Operating system	DOS 2.1 or higher
Memory required	256 K
Disk driver required	1 floppy or a hard drive
Printer required	recommended

Program Available From:
Dale Solomon or Richard Hosmer
Northeastern Forest Experiment Station
University of Maine
Orono, ME 04469

Media: Floppy disk and user's manual

Cost: blank diskette

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DETERMINING FAMILIES OF TREE GROWTH CURVES CONSISTENT WITH STOCK TABLE DATA

A. J. Thomson[1]

ABSTRACT. Stock tables are commonly used to show the distribution of tree sizes at different stages of a stand's development. A lodgepole pine stock table is used to illustrate a general method by which a stand table can be disaggregated into tables showing the number of trees which remain in a size class, the number of trees moving to a larger size class, and the number of trees which die. From such tables, a family of individual tree growth curves and survivorships compatible with the original stand table can be generated.

INTRODUCTION

Stock tables give the number of trees in a particular size class at different stages in a stand's development. An entry in the stand table represents a net balance of trees dying, trees remaining in a class from one period to the next, and trees moving up to the class from smaller classes. Once the mortality has been determined from an appropriate species-specific mortality model, the other categories of trees follow.

Assuming that trees do not change their relative ranking in the size distribution, a procedure has been developed which will give the individual tree growth curves and survivorships compatible with the original stock table. Individual tree height growth curves may be determined by assuming a linear height-dbh relationship.

The purpose of this procedure is as follows. Stock tables are often developed for unmanaged stands or stands unimpacted by pests or diseases or management treatments. The data used to construct the stock tables may not include individual tree growth measurements, as it is possible to construct such tables from measurements of size distributions given different average ages and sizes. Growth curves may be determined for that unaffected condition to a particular point in time, and thereafter the curves and survivorships may be modified to reflect pest or management effects. Stock tables can then be generated from the modified data to reflect the impact of the new conditions on the original stock table.

An example of the method is presented based on variable-density yield

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Table 1a. Stems/ha by 2.5 cm dbh class.

Av. dbh	Av. age	total stems	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0
							2.5 cm dbh class					
2.5	20	11834	8438	2615	781	0	0	0	0	0	0	0
5.0	29	8967	3497	2986	1838	619	27	0	0	0	0	0
7.5	44	6043	858	1488	1883	1265	483	66	0	0	0	0
10.0	64	4037	174	497	958	1148	800	363	97	0	0	0
12.5	89	2843	34	134	367	644	738	539	287	100	0	0
15.0	120	2265	0	0	129	281	483	550	435	249	113	25

Table 1b. Mortality by 2.5 cm dbh class and increase in age.

Av. dbh	Av. age	total stems	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0
							2.5 cm dbh class					
2.5	20	11834	2867	0	0	0	0	0	0	0	0	0
5.0	29	8967	1577	1347	0	0	0	0	0	0	0	0
7.5	44	6043	407	706	893	0	0	0	0	0	0	0
10.0	64	4037	75	214	412	493	0	0	0	0	0	0
12.5	89	2843	10	40	111	194	223	0	0	0	0	0

Table 1c. Stems/ha moving to a larger class, by 2.5 cm dbh class.

Av. dbh	Av. age	total stems	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0
							2.5 cm dbh class					
2.5	20	11834	2074	1703	646	0	0	0	0	0	0	0
5.0	29	8967	1062	1213	1168	522	27	0	0	0	0	0
7.5	44	6043	277	562	594	711	394	66	0	0	0	0
10.0	64	4037	65	214	393	404	466	290	97	0	0	0
12.5	89	2843	24	94	245	414	446	435	287	100	0	0

Table 1d. Stems/ha remaining in their 2.5 cm dbh class.

Av. dbh	Av. age	total stems	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0
							2.5 cm dbh class					
2.5	20	11834	3497	912	135	0	0	0	0	0	0	0
5.0	29	8967	858	426	670	97	0	0	0	0	0	0
7.5	44	6043	174	220	396	554	89	0	0	0	0	0
10.0	64	4037	34	69	153	251	334	73	0	0	0	0
12.5	89	2843	0	0	11	36	69	104	0	0	0	0

tables for natural stands of lodgepole pine in Alberta (Johnstone 1976). For a range of site productivity (PI) indices (0.8 (poor) - 1.2 (good)) and density levels, variables such as average dbh, average height, density, basal area and volume were tabulated at 5-year intervals. The tables were also expressed in the forms of equations including one to generate the number of trees in specified frequency ranges of the dbh distribution. Based on a comparison of Johnstone's tables with those of Smithers (1961), Thomson (1987) extended the range of applicability of Johnstone's tables to age 120, with PI values down to 0.7, and for densities up to 2500 stems/acre at age 70. A metric version of these extended tables has been developed and was used to generate the stock table which forms the basis of this presentation.

GENERAL PROCEDURE

STOCK TABLES

The first stage in the procedure for generating individual tree growth curves was to generate the stock table on which they were based. Table 1a shows a stock table developed for an average site (PI=1.0). An initial stand density of 11834 stems/ha at age 20 was used, giving a starting average dbh of 2.5 cm.

Table 1a illustrates several requisites for stock table construction.

a) An appropriate period between rows of the table must be selected. With a fixed age increment, there is only a relatively small change in numbers per class in the later periods, so in this example, ages were selected which gave a 2.5 cm increment in the average dbh.

b) Appropriate class intervals must be selected. The present example was based on increments of 2.5 cm. With larger increments there is less movement of stems from one class to another, while with smaller increments trees may move over several classes from one time period to the next. The optimum class size will vary with the change in average size between successive rows of the table. The class size should be less than or equal to the difference in average size between successive rows.

c) In generating dbh distributions, some classes may have very few trees. As in the present case a density limit may be imposed to avoid "tails" to the distribution representing very few stems/ha.

From one period to the next, there are three alternative states for the trees in a class to enter : (a) a tree may move to a larger class, (b) a tree may remain in the same class, or (c) a tree may die. The same stock table may result from different patterns of mortality and growth.

In the present system, a pattern of mortality is specified. Once the mortality has been determined (Table 1b), the number of stems moving to larger classes or remaining in a class can be derived (Tables 1c,1d). For this lodgepole pine example, mortality was assumed to

occur in the smaller classes, at a rate proportional to the class density, as suggested by Lee (1967), although alternative mortality models could be easily incorporated.

As an example of use of Tables 1a - 1d, consider the tables at age 29 when the average dbh was 5.0 cm. The 9867 live stems are distributed over four dbh classes. Of the 3497 stems in the smallest class, 1577 die before age 44, 1062 grow to enter a larger class, and 858 remain in the smallest class.

GENERATING INDIVIDUAL TREE SIZES

Once the stock table has been produced, individual tree sizes for each row of the table may be generated. Assume that the smallest tree in the distribution is at the lowest limit of the smallest non-zero class and that the largest tree in a class is at the upper limit of the class (e.g., 3.75 cm, 6.25 cm ...). A cumulative distribution may then be produced in which the sizes of the trees at the class limits are known. For trees between the class limits, sizes may be obtained by interpolation.

As an alternative to the above procedure, a Weibull distribution can be calculated (Shifley and Lentz 1985). The size of a tree at a particular percentile of the distribution may then be determined.

INDIVIDUAL TREE MORTALITY

When the individual tree sizes at a particular age have been assigned, mortality over the next period is determined in the following manner. The probability of mortality of a tree in a particular class in that period is obtained from the information contained in Table 1b. Cycling through the trees in a class, mortality occurs first in those tree which grow slower than a specified threshold rate, and thereafter a random number is compared with that probability to determine if a particular tree dies. This procedure is continued until the required level of mortality for the class has been reached. For each period of the stock table, therefore, the distribution of individual living tree sizes is produced.

TREE DIAMETER GROWTH CURVES

From one period to the next it is assumed that a trees' relative rank in the distribution does not change, thus the j'th surviving tree from period i grows to become the j'th tree of the distribution in period i+1 (Figure 1). Table 2 indicates the form of the output array from the procedure.

(a)	dbh IN PERIOD i	3.57	3.57	3.58	3.58	3.58	3.59	3.59
(b)	ASSIGN MORTALITY	3.57	0.0	0.0	3.58	0.0	3.59	3.59
(c)	LINK SURVIVING TREES							
	dbh IN PERIOD i + 1	4.72	4.72	4.72	4.73	4.73	4.73	4.74

Figure 1. Diagram of the method of linking diameter distributions in successive periods. a) Dbh distribution at start : all trees alive. b) Trees dying by start of next period are set to zero, and c) surviving measurements of first period are linked to measurements of next period.

TREE HEIGHT GROWTH CURVES

Once the individual tree dbh growth curves have been determined, height growth curves can be obtained by developing height-dbh relationships for each period if the average tree height is known. A reference point on the height-dbh curve is obtained from the site index height (top height) which is the average height of the largest 100 stems/acre (247 stems/ha). The average dbh of these trees can be obtained from the individual tree size distribution. A linear height-dbh relationship is assumed. Figure 2 illustrates a set of possible lines passing through the reference point. Heights for each tree were estimated assuming a line passing through the reference point with slopes ranging from 0.025 to 0.800, and the average height using each slope computed. The ratio of the computed average height to the expected average height is used to indicate the appropriateness of that slope value. The ratio of this computed average height to the expected average height is used to indicate the appropriateness of that slope constant. An interpolation procedure is then used to estimate the slope of the slope of relationship which gives a mean height equal to the expected average height, i.e. with a ratio of computed and expected average height equal to 1.0.

DISCUSSION

Changes in the number of trees per size class with age of a developing stand result from varying proportions of trees in a class dying, growing to a larger size class, or remaining in their present class. By

Table 2. Extract from file of individual tree growth profiles. The initial density at age 20 was 11834 stems/ha. Zero's indicate stem mortality.

Tree ranking	Diameter at age 20	29	44	64	89	120
.						
.						
.						
4	1.25	0.00	0.00	0.00	0.00	0.00
5	1.25	1.25	1.25	1.25	1.25	0.00
6	1.25	1.25	1.25	0.00	0.00	0.00
.						
5005	2.73	3.59	0.00	0.00	0.00	0.00
5006	2.73	3.59	5.29	6.91	8.70	10.91
5007	2.73	0.00	0.00	0.00	0.00	0.00
.						
11000	6.20	8.49	10.69	12.58	14.18	16.19
11001	6.20	8.49	10.69	12.58	14.18	16.20
.						
11833	8.75	13.66	16.21	18.72	21.22	26.15
11834	8.75	13.75	16.25	18.75	21.25	26.25

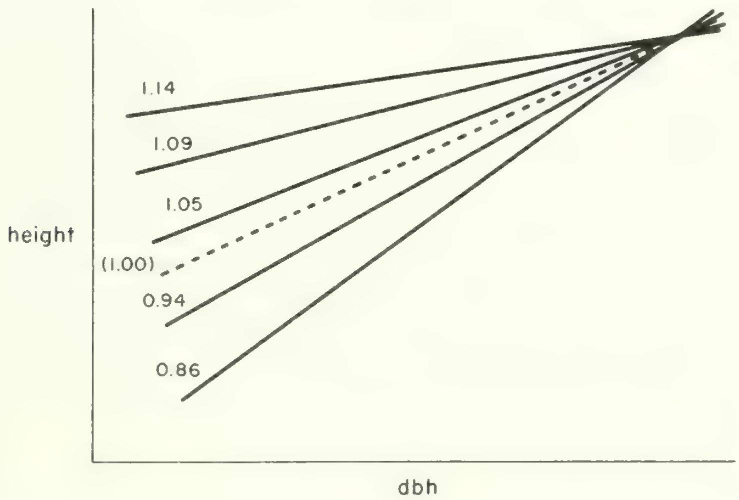

Figure 2. Example of the estimation procedure for height-dbh curves. Solid lines are test relationships and the dashed line is the true relationship. All lines pass through the reference point. The proportion of the calculated and expected average height which results from such test lines is indicated in parentheses.

specifying the pattern of mortality, the numbers growing or remaining in each class can be calculated. Assuming that trees retain their relative positions in the size distribution, sizes in successive periods can be linked such that indivdual tree growth curves compatible with the original size distribution are produced. Once the dbh growth is defined, the height growth can also be determined.

The procedures described allow individual tree growth patterns to be estimated from tables based on data which contained no growth measurements. These individual tree growth curves may then be manipulated to reflect pest and disease effects or forest management practices.

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DEVELOPMENT AND APPLICATION OF A STAND-BASED GROWTH MODEL FOR MIXED HARDWOOD STANDS

David O. Yandle, John R. Myers,
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ABSTRACT. A model for predicting growth in mixed hardwood stands is presented. The model, based on the assumption that future diameter growth is related to past diameter growth, is proposed for projecting the moments and functions of moments of tree diameter frequency distributions over time. Projections are made for stand attributes including basal area, board foot volume, and cubic foot volume in tree distributions of even-aged, mixed-species hardwood stands. The model incorporates a measure of shade tolerance to partially account for species growth differences. Further model enhancements are suggested.

INTRODUCTION

A stand-based growth model for mixed hardwood stands has been developed and tested on two different data sets which have quite different species compositions.

Portability of the model to provide for its application in stands that differ in composition from the species mix in the stands in which the model was developed is achieved by the use of shade tolerance classes. Hardwood species are grouped by tolerance classes and then measures based on the classes are included in the model.

The model is essentially that introduced by Yandle (1978), but with a newly-developed equation for estimation of growth rate and with appropriate forms for ingrowth and mortality.

In this paper we treat only the prediction of single quantities such as average basal area or volume per acre at a future time. Such quantities are predicted by projecting a linear function of one or more moments of the present diameter distribution, without the necessity of first estimating the parameters or other properties of the future distribution. Thus, the characterization of the model as presented in this paper does not fit neatly into either of the categories of parameter prediction model (PPM) or parameter recovery model (PRM) as given by Hyink and Moser (1983). However, extensions of the model that predict for other than point functions are in the PRM category. The prediction of a future probability density function (p.d.f.) for

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diameter or prediction of areas (distribution function) representative of proportions in given diameter classes have been studied and will be presented elsewhere.

THE PROJECTION METHOD

Stand-based models are based on current stand measurements as usable past measurements or quantifiable stand history are normally unavailable. In order to use only current stand information, we can make use of the fact that the average past periodic growth of a tree is a relatively good index to its future growth. That is, trees that have had better growth in the past will have better growth in the future than trees that had less growth in the past. This is not to say that the rate of growth of a given tree in the future will be the same as in the past but only that those trees that have been more successful than their competitors in the past can be expected, on the average, to be more successful in the near future. Since present diameter is the sum of past diameter growth, we can express this idea in the following relationship:

$$I_d = b'K'D_1 \tag{1}$$

where I_d = average dbh increment over L for trees with $D_1 = D_{1i}$
D_{1i} = dbh of tree i at present time
b' = proportionality constant (slope)
K' = L/A
L = length in years of the projection period
A_i = age in years of tree i (A_i = A for even-aged stands)

The dbh increment, during the period L, for a given tree is given by

$$Y_{1i} = I_d + e_{1i} = b'K'D_{1i} + e_{1i} \ , \tag{2}$$

where e_{1i} is a random component of dbh growth by which tree i deviates from the mean of all trees having the same initial dbh. Thus the dbh at the end of the projection period is:

$$D_{2i} = D_{1i} + Y_{1i} = (1 + b'K')D_{1i} + e_{1i} \tag{3}$$

In general, a direct mathematical treatment of the transformation expressed by equation (3) will require a complete handling of the probability density functions for b', D_1, and e_1 (or their joint density function, if they are not all independent.) A direct analytic solution will be difficult, if not competely intractable; however, the expected value of the future diameter, $E[D_2]$, can be expressed as a function of the present diameter, D_1:

$$E[D_2] = E[(1 + b'K')D_1 + e_1] \ .$$

If $E[e_1] = 0$ is assumed and b' replaced with an unbiased estimator, $\hat{b}'$, then an estimate, $\bar{D}_2$, of $E[D_2]$ is given by:

$$\bar{D}_2 = (1 + \hat{b}'K')E[D_1] \ . \tag{4}$$

Thus, the mean, $E[D_2]$, of the future diameter distribution can be

directly estimated as a function of the mean, $E[D_1]$, of the present diameter distribution.

Returning to equation (1), we can examine the relationship for the squared diameter in a manner analogous to that developed for diameter. Adding D_1 to each side of equation (1) and squaring each side gives

$$(I_d + D_1)^2 = (1 + b'K')^2 D_1{}^2 \ . \tag{5}$$

Also, note that as the diameter increases from D_1 to $(D_1 + I_d)$, the square of diameter increases from $D_1{}^2$ to $(D_1 + I_d)^2$, thus the increment of the square of diameter can be expressed as:

$$I_{dd} = (I_d + D_1)^2 - D_1{}^2 \ . \tag{6}$$

Thus, equation (5) can be converted by subtracting $D_1{}^2$ from each side to give

$$I_{dd} = [(1 + b'K')^2 - 1]D_1{}^2 \ . \tag{7}$$

Further, if in equation (7) we set

$$b = (1/K')[\ (1 + b'K')^2 - 1\ ] \tag{8}$$

and $K = K'$, (9)

then

$$I_{dd} = bKD_1{}^2 \ . \tag{10}$$

Thus, the direct relationship for the increment of the square of diameter as a function of $D_1{}^2$ is expressed in the same format as for diameter increment. We now see that the diameter squared for tree i at the end of the projection period is

$$D_{2i}{}^2 = (1 + bK)D_{1i}{}^2 + e_{2i} \tag{11}$$

where e_{2i} is a random component of the growth, of the square of diameter, by which tree i deviates from all trees having the same initial diameter. Thus, the expected value, $E[D_2{}^2]$, of the square of diameter in the future distribution of the square of diameter can be expressed directly in terms of the expected value of $D_1{}^2$ in the present diameter distribution as

$$E[D_2{}^2] = (1 + bK)E[D_1{}^2] \ , \tag{12}$$

and for $E[e_2] = 0$ and $\hat{b}$ an unbiased estimate of b, an estimator, $\overline{D}_{22}$, of $E[D_2{}^2]$ is given by

$$\overline{D}_{22} = (1 + \hat{b}K)E[D_1{}^2] \ . \tag{13}$$

We also have need to examine other estimators that are constructed as functions of tree diameter or diameter squared. First, because basal area is the square of diameter multiplied by pi/576, equation (13) can be modified as follows to give an estimator of basal area per acre at the end of the projection period:

$$\hat{B} = (N/S)(pi/576)(1 + \hat{b}K)E[D_1{}^2] \ , \tag{14}$$

where N = number of trees in the stand at the end of the period
S = size of the stand in acres.

Other stand attributes that can be expressed as functions of tree diameter are also of interest. For example, for known coefficients a_1 and a_2, let

$$F_i = a_1 + a_2B_i$$

$$= a_1 + a_2[(pi/576)(1 + bK')D_{1i}^2 + e_{2i}] , \quad (15)$$

then a per-acre estimator of F_i is given by:

$$\hat{F} = (N/S)[a_1 + a_2(pi/576)(1 + \hat{b}K)E(D_1^2)]$$

$$= (N/S)a_1 + a_2\hat{B} . \quad (16)$$

It is obvious that if F expresses a "local-use" volume equation, then equation (16) is an estimator of volume per acre at the end of the projection period.

APPLICATIONS

Two sets of growth data were obtained for use in the study: one set was provided by the Muskingum Watershed Conservancy District, an Ohio public corporation engaged in land and water management; a second set was furnished by the U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Fernow Experimental Forest, near Parsons, West Virginia.

Muskingum Watershed Data

The Muskingum Watershed Conservancy District manages forest lands located in the Muskingum River watershed in east central Ohio. Permanent 1/5-acre plots located on these lands have been remeasured on a regular periodic basis for more than 25 years. The present study has made use of a part of these data for plots located in even-aged, mixed hardwood stands, and covering two 10-year growth periods: 1960 to 1970 and 1970 to 1980.

Both stand and individual tree measurements and information were recorded at each remeasurement. Plots that had had major disturbance such as recent logging or known disease losses were omitted from this study, as were plots containing too few trees to be useful in the model fitting process. Plots that were used contained at least 10 merchantable trees (dbh equal to or greater than 5.5 inches) and a minimum of 3 sawtimber sized trees (dbh equal to or greater than 11.5 inches.)

The reduced data set was comprised of 63 plot records each of which consisted of measurements made at the beginning and again at the end of a 10-year period. The 63 plots were randomly divided into 2 groups. One group of 32 plots was used for model development and a second group of 31 plots was reserved for later use in model validation.

Fernow Experimental Forest Data

The Fernow Experimental Forest is in the mountains of north central West Virginia and is located approximately 140 miles southeast of the Muskingum watershed.

The method of measurement and collection of the Fernow data differs from that used to obtain the Muskingum data. The Fernow data set consists of 15 plots in previously unmanaged stands. Plot size is variable, ranging up to several acres, with 100-percent tree inventories made at each measurement time. Diameters are recorded by 2-inch classes and tree counts are summarized on a per-acre basis. Periods between remeasurements were of variable length. Individual tree identity was not maintained from one remeasurement to the next.

Fitting the Model

The process of fitting the model is one of using the stand variables to estimate the slope, b, in equation (8). In order to do this, it is necessary, in each plot, to have the individual tree diameters at both the start and the end of the period, and thus the perodic increment of growth. This form of information is available in the Muskingum data, and thus, that data was used for developing the model fit.

The first step in the analysis was to calculate, separately for each of the first 32 Muskingum plots, values of the slope, b, using the individual tree data within each plot. Because the stands are considered to be even-aged and the projection period is fixed at 10 years, the value of K = L/A was treated as a constant, thus the 32 slopes were each expressed as Z = Kb to incorporate the constant.

The next step was to determine how to use stand variables to predict Z. Regression analyses using the 32 values of Z as observations of the dependent variable and various combinations of stand variables as independent variables were made. The final regression form that was determined is

$$\hat{Z} = 0.01191496 - 0.00111439(IBA) - 0.00377597(TBA) - 0.00254829(MBA) + 0.00356842(SI) - 0.00075542(NT) + 0.00217498(AGE) + 0.00743148(QMD) \quad (17)$$

where IBA = basal area of intolerant species as a percent of the basal area of all trees of merchantable size
TBA = basal area of tolerant species as a percent of the basal area of all trees of merchantable size
MBA = basal area of all trees of merchantable size
SI = site index
NT = number of merchantable trees at start of period
AGE = age in years of the stand
QMD= quadratic mean diameter of treesoftolerant species.

All variables in the equation are on a per-acre basis, measured at the beginning of the projection period. Shade tolerance ratings are those given in the Forestry Handbook (Wenger, 1984). The coefficient of

determination for the fitted regression was 0.65.

Applying the Model to the Muskingum Data

The model was applied to each of the 31 reserved Muskingum plots to predict growth for the sawtimber class.

Ingrowth into the sawtimber class for each plot was estimated by calculating the minimum diameter that any tree less than sawtimber size at the start of the period must have in order that it be expected to reach sawtimber size at the end of the period. This was accomplished by calculating $\hat{Z}$ for the plot and using an algebriac modification of equation (4) such that

$$\text{dbh(min)} = 11.5 \; / \; [1 + \hat{Z}]^{1/2} \, ,$$

where the term, $1 + \hat{B}'K'$, in equation (4) is replaced by the estimator $[1 + \hat{Z}]^{1/2}$ for the plot. Any tree on the plot with a diameter at the start of the period equal to or greater than dbh(min) was included as ingrowth in the projections for the plot. All plot values were converted to a per-acre basis after adjusting for ingrowth to permit adding an adjustment for mortality. The per acre conversion also facilitated the fitting of the Johnson S_B p.d.f. (Johnson, 1949) for the projection process. (The Wiebull p.d.f. was also tried in the initial testing, but was found to be not as satisfactory as the Johnson in this application.)

Actual mortality percentages in the 32 Muskingum plots used to fit the model were calculated for each 1-inch dbh class. A Johnson S_B p.d.f. was fitted to these points to produce a smooth mortality curve. Mortality values read from this curve were applied to the 31 Muskingum plots for which predictions were made.

The per-acre values adjusted for estimated ingrowth and mortality were then fitted by the maximum likelihood method for the Johnsons S_B p.d.f. (Schreuder et al, 1978) and the expected values, E(DBH) and E(DBH^2) obtained. These values were then used to make growth projections for sawtimber basal area and board-foot volume per acre.

Applying the Model to the Fernow Data

The minimum dbh used to determine estimated ingrowth for the Fernow data was calculated as it was for the Muskingum data; however, it was used to determine the percentage of the 2-inch dbh class that would be moved forward, rather than for individual trees. This was necessitated because individual trees were not identified at both the beginning and end of a growth period.

The mortality curves developed from the Muskingum data were refit on a 2-inch dbh basis and directly applied to the Fernow data.

Variations from the shade tolerance ratings in the Forestry Handbook are given in Trimble (1975) for species in Appalachian hardwood stands and were used for the Fernow stands.

Basal area predictions were made for the sawtimber class and for the class of all merchantable trees. Volume predictions were not made because there is no actual volume data for comparisons.

Equation (17) as developed from the Muskingum data -- without changes in either the variables or the coefficients -- was applied to estimate the required slopes needed to make the growth projections for the Fernow stands. All other steps in the projection were carried out the same for the Fernow data as has been described for the Muskingum data.

Coefficients of variation shown in Table 1 are on a per-plot basis - not for means - and were calculated from the differences in predicted and actual plot values.

RESULTS AND DISCUSSION

The overall results as summarized in Table 1. indicate that the model is well-behaved and is a good predictor of growth for mixed hardwood stands.

The model, including the slope estimation equation (17) as developed with the first set of Muskingum data, performed better when applied to the Fernow data than it did when applied to the validation set of Muskingum data. Two points concerning this result should be noted.

First, the use of measures of shade tolerance as variables in the growth-rate part of the model does provide the necessary flexibility to apply the model in areas having species composition different from that in the area from which the development data is obtained. A parallel attempt to develop a model in the same overall manner but with inclusion of measures of individual species yielded good results when the model was applied to the validation set of Muskingum plots, but failed when applied to Fernow plots which have different species composition.

Secondly, the better performance of the model when applied to the Fernow data than with the validation set of Muskingum data is due to the fact that each of the Fernow plots contained a number of trees sufficient to adequately characterize the initial diameter distribution of the plot, whereas this was not true for all Muskingum plots.

The need for plots in which individual trees are identifiable over time is essential for the development of the slope equation. However, as in the Muskingum data, plot data can be suitable for that purpose, but at the same time small plot size may result in some plots having too few trees to permit an adequate definition of the diameter distribution in that part of the model.

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TABLE 1. Results of the projections.

Projected quantity	Number of plots	Average value actual	Average value predicted	Coefficient of variation (percent)
Muskingum data				
Basal Area (sawtimber)	31	55	55	17
Basal Area (sawtimber)	17	75	74	13
Board-foot volume	31	6165	6076	19
Board-foot volume	17	8567	8287	16
Fernow data				
Basal Area (all merch.)	9	115	113	14
Basal Area (all merch.)	6	137	145	8
Basal Area (sawtimber)	9	83	83	12
Basal Area (sawtimber)	6	109	114	8

All basal areas are in units of square feet per acre, board-foot volumes are per-acre values.

For Muskingum data: values are shown for the total of 31 plots and for the 17 of those which had 35 or more trees.

For Fernow data: values are shown for the 9 plots that had 10-year growth periods, and for the 6 of those which had stands 20 years or more in age at the start of the period.

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CONSISTENT GROWTH AND YIELD PREDICTION THROUGH INTEGRATION OF WHOLE STAND AND DIAMETER DISTRIBUTION MODELS.

Sun Joseph Chang[1]

ABSTRACT. Past efforts in integrating the whole stand and diameter distribution models have largely ignored the proper curvature of the basal area equation and its consequence through parameters recovery on the yield prediction surface. In this paper, a guasi-concave function is employed to estimate the basal area growth equation and the resultant yield predictions are then examined for desirable properties. Results of the study show that, with the parameter recovery procedure, proper curvature of the basal area equation does not necessarily ensure desirable properties in the yield prediction surface.

INTRODUCTION

Soon after Bailey and Dell (1973) published the methodology to quantify diameter distribution with the Weibull function, researchers in forest growth and yield modeling realized that the parameters of the Weibull function can be recovered from the whole stand attributes. Papers published since 1973 show a long list of successful applications of the parameters recovery technique to many different situations (Smalley and Bailey 1974a,b; Strub and Burkhart 1975; Clutter and Belcher 1978; Feduccia et al 1979; Dell et al 1979; Hyink 1980; Frazier 1981; Matney and Sullivan 1982; Cao et al 1982; Burkhart and Sprintz 1984; Borders and Bailey 1986). Since stand level attributes play a critical role in the recovery of the parameters of the Weibull function for diameter distribution, the estimation of stand level attributes assumes unparalleled importance. Little attention, however, has been given to the functional form and shape of these stand level attributes. Indeed, as Burkhart, Cao, and Ware (1981) pointed out most of the stand models are highly empirical "best fit to the data". As a result, the diameter distribution models may display abnomalities in yield predictions as reported by Chang (1984).

Forest economists, on the other hand, have been trying to introduce the concepts of the production functions into the development of the growth and yield model. (Jackson 1980; Nautiyal and Cuoto 1983; Chang 1984). Their main point is to establish the input-output relationship between yield as the output of management decision variables such as rotation age and planting density. Chang (1984) further suggested that the timber yield should possess the following desirable properties:

1. The yield surface is guasi-concave with respect to both stand age and planting density.
2. The yield for any combination of stand age and planting density is also quasi-concave with respect to site index.

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This paper reports the development of a compatible whole stand and diameter distribution model based on estimates of basal area employing a quasi-concave production function. The purpose is to determine if a smooth and well-behaved basal area equation would ensure the desirable smoothness and proper curvature in the yield prediction.

DATA AND METHOD.

The data used to estimate the stand level attributes are those published in Smalley and Bailey (1974a) for loblolly pine in Tennessee, Alabama and Georgia highlands. The site index ranges from 40 to 70 feet at an increment of 10 feet (base age 25 years); planting density varies from 500 to 2500 per acre with an increment of 250 stems per acre; stand age ranges from 10 to 40 years at an increment of 5 years. Altogether, there are 252 observations.

The development of the model consists of two steps. The first step involves the estimation of stand-level attributes with regression technique. The second step determines the Weibull parameters so that the resulting stand basal area and average dbh estimates are identical to those predicted from the stand level model. By linking these two stages, the size-class distribution information will provide aggregate basal area value that are consistent with the over-all stand level attributes.

STAND LEVEL MODEL.

With the exception of the basal area and average stand diameter, other stand level attributes such as height growth equation and volume equations used in this paper are the same as those in Smalley and Bailey (1974a).

Basal Area Estimation

The basal area is estimated with the following equation:

$$BA = B_0 \mathrm{Exp}\ (B_1/t^2 + B_2/(t*m) + B_3/(t*SI) + B_4/SI^2) \qquad (1)$$

where BA is the basal area of the stand,
t is the age of the stand
m is the planty density per acre
SI is the site index and
B_0, B_1, B_2, B_3, B_4 are coefficients
to be estimated with $B_0 > 0$ and $B_1 - B_4$ less than zero.

In equation 1, B_0 Exp (B_4/SI^2) represents the maximal basal area a stand could attain given a particular site index. Since B_4 is less than zero, $B_0\mathrm{Exp}(B_4/SI^2)$ increases with increasing SI, first at an increasing rate and then at a decreasing rate. The coefficient B_1 determines the basic curvature of the basal area growth curve. This basic basal area growth curve is then modified for the planting density with B_2. Since B_2 is less than zero, the smaller the planting density the flatter the basal area growth. The same basic basal area growth is also modified for the site index with B_3. Again, since B_3 is less than zero, the smaller the site index the flatter the basal area growth curve.

Normally, equations 1 can be easily estimated by regressing the log-transformed equation:

$$\ln BA = \ln B_0 + B_1/t^2 + B_2/(tm) + B_3/(tSI) + B_4/SI^2 \quad (2)$$

with the linear regression subroutines of any standard statistical package. In this case, however, since all the data are generated from a computer program the hetero-scadasticidy typically associated with basal area no longer exists. It is, therefore, more appropriate to obtain the non-linear estimates of coefficients for equation 1. The result of such a regession is as follows:

$$BA=317.8283 \operatorname{Exp}(-25.4545/t^2-4991.7070/(tm)-49.3858/(tSI)-872.7487/SI^2) \quad (3)$$

Average Diameter Estimation

Although it is possible to develop an equation to predict the average diameter of any particular stand such an approach unfortunately may cause difficulties later in the recovery of Weibull parameters. As Burk and Newberry (1986) have suggested that in the process of Weibull parameters recovery, the mean diameter of the stand $\bar{X}$ must be less than or equal to the quadratic mean diameter of the stand $(\overline{X^2})^{\frac{1}{2}}$. Independent estimations of basal area and average diameter of the stand provide no guarantee that $\bar{X} \leq (\overline{X^2})^{\frac{1}{2}}$ would indeed hold all the time. As a matter of fact, preliminary work on Weibull parameters recovery for this project failed because $\bar{X} \leq (\overline{X^2})^{\frac{1}{2}}$ was not met.

In order to ensure that $\bar{X} \leq (\overline{X^2})^{\frac{1}{2}}$ always hold often a regession of $(\overline{X^2})^{\frac{1}{2}} - \bar{X}$ on some independent variables was carried out to enable the prediction of $\bar{X}$ based on basal area. (See, for example, Cao, Burkhart and Leming, Jr. 1982). Examination of the $(\overline{X^2})^{\frac{1}{2}} - \bar{X}$'s shows that with the exception of one zero they are either .1 or .2 and average to be .1266. Thus the simplest model possible

$$\bar{X} = (\overline{X^2})^{\frac{1}{2}} - .1266 \quad (4)$$

was chosen to represent the average diameter of the stand.

RECOVERY OF DIAMETER DISTRIBUTION FROM STAND ATTRIBUTES.

The three parameter Weibull pdf employed in this paper to describe the diameter distribution is:

$$f(X) = (c/b)((X-a)/b)^{c-1}\exp(-((X-a)/b)^c) \quad (5)$$

where

a is the non-negative location parameter
b is the scale parameter
c is the shape parameter
X is the diameter random variable and $X \geq a$.

The first two moments of the Weibull distribution are

$$E(X) = \bar{X} = a + b\Gamma(1 + 1/c) \quad (6)$$

$$E(X^2) = \overline{X^2} = a^2 + 2ab\Gamma(1 + 1/c) + b^2\Gamma(1 + 2/c) \quad (7)$$

where Γ represents the gamma function and since English units are used

$$\overline{X^2} = BA/(.005454N) \tag{8}$$

where N is the number of trees per acre.

$$S^2 = \overline{X^2} - \bar{X}^2 = b^2 \left(\Gamma(1 + 2/c) - \Gamma^2 (1 + 1/c)\right) \tag{9}$$

and coefficient of variation CV

$$CV = \frac{S}{\bar{X} - a} = \frac{\left(\Gamma(1 + 2/c) - \Gamma^2(1 + 1/c)\right)^{\frac{1}{2}}}{\Gamma (1 + 1/c)} \tag{10}$$

Given a specific value of a as well as estimates of $\bar{X}$ and $\overline{X^2}$, the value for "C" in equation (10) can be solved fairly easily with many zero finding subroutines in numerical analysis. Once C is known "b" is solved with

$$b = (\bar{X} - a)/\Gamma(1 + 1/c) \tag{11}$$

Once the three parameters a, b, and c are obtained to specify the Weibull distribution, diameter distribution is generated to obtained the basal area according to

$$BA = .005454N \sum_{X_i = 1}^{\infty} X_i^2 f_i \tag{12}$$

where N is the number of trees
X_i is the midpoint of the ith dbh class
$f_i = F(X_i + .5)-F(X_i - .5)$ is the proportion of trees in the ith dbh class and
$F(X) = 1- \exp(-((X -a)/b)^c)$ is the Weibull cumulative distribution function with parameter a, b, and c.

If the basal area obtained through calculation of equation (12) does not equal that of the whole stand estimate, a refined "a" will be computed and the parameters recovery procedure repeated until basal area figure from equation (12) is within .02 square feet of the stand level estimate of the basal area.

Table 1. Yield and Diameter Distribution of a Site Index 70 Stand Age 25 with an Initial Planting Density of 750 Stems per Acre.

SITE INDEX 70
750 STEMS PER ACRE PLANTED

AGE	AV DOM HT	DBH	STEMS PER ACRE	BASAL AREA	AV HT	ALL TREES, TOTAL STEM O B	ALL TREES, TOTAL STEM I B	5-INCH CLASS AND GREATER TO O B. TOPS OF — 2 INCHES O B	2 INCHES I B	3 INCHES O B	3 INCHES I B	4 INCHES O B	4 INCHES I B
25	70	7	109 9	29 4	59 0	874 9	636 2	840 9	636 2	822 9	630 5	779 6	596 5
		8	142 8	49 8	62 0	1559 5	1134 4	1494 8	1134 4	1473 7	1134 4	1423.0	1099.3
		9	95 3	42 1	65 0	1380 7	1004 5	1320 9	1004 5	1308.7	1004 5	1279.4	994 3
		10	54 2	29 6	66 0	983 5	715 6	939 8	715 6	933 9	715 6	920 0	715 6
		11	27 9	18 4	68 0	630 5	458 8	601 9	458 8	599 6	458 8	594 1	458 8
		12	13 3	10 5	69 0	363 4	264 5	346 7	264 5	346 0	264 5	344 2	264 5
		13	6 0	5 5	71 0	197 2	143 5	188 1	143 5	187 9	143 5	187 5	143 5
		14	2 6	2 7	72 0	99 0	72 1	94 4	72 1	94 4	72 1	94 4	72 1
		15	1 0	1 3	73 0	47 0	34 2	44 8	34 2	44 8	34 2	44 8	34 2
		16	0 4	0 6	73 0	21 0	15 3	20 0	15 3	20 0	15.3	20 0	15 3
		17	0 2	0 2	74 0	9 1	6 6	8 6	6 6	8 6	6 6	8 6	6 6
		18	0 1	0 1	75 0	3 8	2 7	3 6	2 7	3 6	2 7	3 6	2 7
		19	0 0	0 0	75 0	1 5	1 1	1 4	1 1	1 4	1.1	1 4	1.1
		20	0 0	0 0	76 0	0 6	0 4	0 6	0 4	0 6	0 4	0 6	0 4
		21	0 0	0 0	76 0	0 2	0 1	0 2	0 1	0 2	0 1	0.2	0 1
		22	0 0	0 0	77 0	0 1	0 1	0 1	0 1	0 1	0 1	0 1	0 1
			-----	-----		------	------	------	------	------	------	------	------
			453 6	190 2		6171 8	4490 1	5906 7	4490 1	5846 3	4484 3	5701 4	4405 1

MEAN DIA 8 6 INCHES. WEIBULL PARAMETERS A= 6 72, B= 2 08, C= 1.31

RESULTS AND DISCUSSION

When the above procedure is carried out, Weibull diameter distribution based on stand level attributes are obtained. A typical result is shown in Table 1. When site index is 70, stand age 25, and planting density 750, stand level estimates of basal area and average diameter are 190.23ft^2 and 8.64 inches respectively. The corresponding figures from the parameter recovery procedure are, after rounding, 190.2ft^2 and 8.6 inches respectively. When the yield for total stem are tabulated by site index and stand age for a planting density of 750 stems per acre (Table 2), some interesting pattern emerges. As expected, the basal area figures and changes in basal area as a result of changes in

Table 2. An analysis of Basal Area and Total Stem Yield Growth for Various Site Indices (Planting Density 750 Stems/Acre).

Age	Basal Area	Basal Area Increment	Total Stem Yield	Yield Increment
Site Index = 70				
10	98.8	46.9	1644.7	1748.8
15	145.4	27.3	3292.9	1460.4
20	172.7	17.5	4853.3	1318.6
25	190.2	12.1	6171.9	1102.4
30	202.3	8.8	7274.3	1012.9
35	211.1	6.7	8287.2	928.3
40	217.8		9215.5	
Site Index = 60				
10	91.5	43.8	1292.9	1363.5
15	135.3	25.7	2656.4	1139.7
20	161.0	16.5	3796.1	1086.2
25	177.5	11.5	4882.3	896.6
30	189.0	8.3	5778.9	738.2
35	197.3	6.3	6517.1	748.7
40	203.6		7260.8	
Site Index = 50				
10	80.9	39.4	935.8	1022.4
15	120.3	22.2	1938.2	931.5
20	143.5	15.0	2869.7	688.5
25	158.5	10.4	3558.2	658.6
30	168.9	7.6	4216.8	541.1
35	176.5	5.8	4757.9	500.8
40	182.3		5258.7	
Site Index = 40				
10	64.9	32.3	618.8	644.5
15	97.2	19.3	1263.3	520.1
20	116.5	12.5	1784.4	490.5
25	129.0	8.6	2273.9	448.7
30	137.6	6.4	2722.6	298.4
35	144.0	4.9	3021.0	315.7
40	148.9		3336.7	

stand display the desirable smooth curvature. The yield for total stems also appears to have the desirable property when site indices are 70 and 50 respectively. When site indices are 60 and 40, changes in yield as a result of changes in stand age decline smoothly until age 35 and rebound between age 35 and 40. While the magnitude of the rebound is not particular significant, they do show that the yield predictions are not as smooth as one would like them to be.

As shown in Table 3, the effect of different planting densities are examined at various ages, when the site index is 70. As Chang (1984) pointed out, when the yields of two stands with different planting densities are compared, the current annual increment and/or the periodic annual increment of the stand with a higher planting density should ascend faster, reach a peak at an earlier age and descend more precipitiously afterwards. The PAI's in Table 3 show that such is indeed the case until age 30. Between age 30 and 35, the stand with an initial planting density of 1500 stems per acre, contrary to the theoretical result, outgrows that of 750 stems per acre. Again, while the magnitude of the problem may not seem significant, it does point out the short-coming of the growth characteristics of the model.

Table 3. The Effect of Planting Densities on Stand Yield and Periodic Annual Increment. (Site Index 70)

	Planting Density = 750 Stems/A		Planting Density = 1500 Stems/A	
Age	Yield	PAI	Yield	PAI
10	1644.7	1748.2	2272.7	1913.8
15	3392.9	1460.4	4186.5	1492.2
20	4853.3	1318.6	5678.7	1250.3
25	6171.9	1102.4	6929.0	1049.0
30	7274.3	1012.9	7978.0	1023.0
35	8287.2	928.3	9001.0	928.1
40	9215.5		9929.1	

Table 4. The Incremental Effect of Planting Densities on Basal Area and Total Yield for a 20 Year-old Stand. (Site Index 70)

Planting Density	Basal Area	Change in Basal Area	Total Yield	Change in Total Yield
500	146.3	26.4	4123.9	729.4
750	172.7	15.0	4853.3	315.6
1000	187.7	9.6	5168.9	371.5
1250	197.3	6.7	5540.4	138.3
1500	204.0	4.9	5678.7	23.7
1750	208.9	3.8	5702.4	60.8
2000	212.7	2.9	6012.7	249.5
2250	215.6	2.4	6054.4	41.7
2500	218.0			

When the effect of successive increment in planting density is examined, the increment in yield as presented in Table 4 shows a much more serious problem. As the planting density increases from 500 to 2500 the increment in yield, rather than displaying a smooth decline, shows wide fluctuations. The most serious ones are the big drop between 750 and 1000 stems and the jump between 2000 and 2250 stems.

CONCLUSION

The focus of this paper is to adopt a guasi-concave function to the estimation of the basal area and to apply the parameters recovery technique to obtain the diameter distribution under Weibull function. The intention is to see if the proper curvature in the basal area growth function would ensure the smoothness and proper curvature of the total yield of the stand. The results above have shown that at least for the Smalley and Bailey model examined, the former does not necessarily ensure the latter. While the results does not shed light on the causes of such short coming - two causes seems plausible. First, it may be a problem inherent to the procedure of parameters recovery for Weibull distribution. Second, it is quite likely that the volume equations used in the model are responsible for the problem. As the growth and yield model becomes more complicated it also places more emphasis on the very basis of the model. In this light, volume equations in general clearly deserve more careful scrutiny.

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MODELING VOLUME GROWTH FOR ARIZONA'S PINYON-JUNIPER FORESTS

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ABSTRACT. Volume growth was modeled for uneven-aged pinyon-juniper stands. Growth data were collected at 91 locations throughout northern Arizona in juniper dominated stands. At each location trees were measured for basal area growth and current volume using nondestructive methods. Equations were developed to project future basal area and future volume. Input variables for the equations were initial stand basal area, elapsed time and a "site index" measurement. The equations were combined in a model to provide a rough guide to cubic-foot volume production for short-term projections. Results indicate most stands will never produce more than 10 cubic feet of wood per acre per year.

INTRODUCTION

Pinyon-juniper woodlands occupy about 48 million acres in the Western United States (Burns 1983). Pinyon-juniper sites are among the most arid of any forest type in the United States. Past management emphasized tree removal and replacement with range forage. Recent interest in fuelwood sources and passage of the Forest and Rangeland Renewable Resources Planning Act of 1974 have created new needs for pinyon-juniper woodland information.

The Forest Survey Project at the Intermountain Research Station, USDA Forest Service, now inventories pinyon-juniper woodlands in most of the counties in the States it surveys (Figure 1). Volume growth is a key component of these inventories. Usual practice for volume growth estimation in a forest inventory requires diameter growth and height growth measurement. For each growth variable, beginning and ending measurements are then used in a volume equation to get volume for two points in time. The difference between the two volumes is volume growth.

However, it is impractical to use this approach for every tree in a large pinyon-juniper inventory because diameter growth and height growth are difficult to measure in the field. Pinyon-juniper diameter growth rings are most easily identified on sanded cores or cross-sections under magnification. Height growth measurement also requires growth ring identification in destructive stem analysis procedures.

Instead of direct tree growth measurements on all trees, a model was sought to estimate pinyon-juniper volume growth for the 1985 forest

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survey of Arizona (USDA 1985). A whole stand growth model, rather than a more detailed individual tree growth model, was sufficient to meet this information need.

Choice of model components was simplified by field observation of tree heights. Few trees in most stands (in the areas inventoried in Arizona) differed in total height once the trees exceeded 6 to 8 inches in basal diameter at the root collar (DRC). This led to the assumption that height growth probably has little effect on short-term volume growth projections. Therefore, the growth modeling focused solely on diameter growth.

Because the mean age range (142 years) of stands inventoried was large, even exceeding the mean stand age (125 years), an uneven-aged modeling approach from Moser and Hall (1969) was selected. This required developing basal area growth and stand volume prediction equations.

DATA

Data to estimate model parameters came from trees on 91 plots (Figure 2) randomly selected from 300 inventory plots established in Arizona in

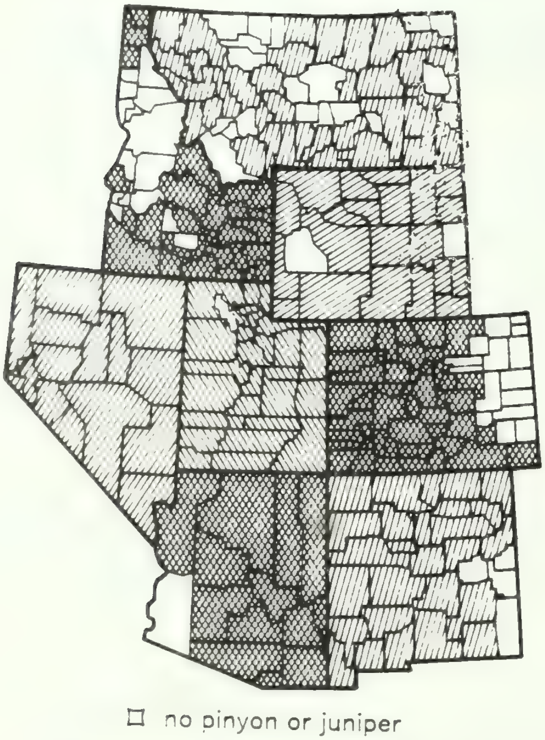

Figure 1. Most counties within the Rocky Mountain States have an occurrence (shaded areas) of pinyon or juniper trees (adapted from Little, 1971).

Figure 2. Locations of 91 study plots.

1985 (USDA 1985). All land ownerships were sampled except the Navajo, Hualapai, Havasupai, Fort Apache, and San Carlos Indian Reservations and all National Forests except the western half of the Prescott. In retrospect, the excluded areas probably included Arizona's most productive pinyon-juniper woodlands.

Plots were a fifth acre in size when crown cover of the surrounding stand was less than 30 percent, and a tenth acre when crown cover was more than 30 percent. All trees that forked at the root collar were measured using a calculated equivalent diameter (EDRC) instead of DRC:

$$EDRC = \sqrt{\sum_{i=1}^{n} D_i^2} \quad (1)$$

where:

D_i = basal diameter of each stem

n = number of basal stems 1.5 inches or larger

Trees not having at least one stem 3 inches DRC or larger were not measured.

Ten-year radial DRC growth was determined from two core samples per tree from about seven trees per plot. Core samples were sanded and growth was measured under magnification. Tree ages were determined for five trees per plot. Volume was estimated for about six trees on each plot by visual segmentation, which is a method to count numbers of wood segments within a tree (Born and Chojnacky 1985). Volume for each tree included wood and bark of all stems and branches larger than 1.5 inches in diameter. Both live and dead wood were included.

Numbers of trees and species sampled were 608 Juniperus osteosperma (Torr.) Little, 356 J. monosperma (Engelm.) Sarg., 24 J. deppeana Steud., 288 Pinus edulis Engelm., and 54 P. edulis var. fallax Little.

All tree-level data were combined for each plot and expressed as per-acre estimates. Those measurements based on subsamples, diameter growth and volume, were expanded to per-acre estimates using regression sampling estimators.

MODELING

The uneven-aged stand growth model taken from Moser and Hall (1969) is based on the ratio of cumulative basal area (BA) growth change expressed in differential notation:

$$d\,BA/dt = f(BA) \quad (2)$$

If the right hand side of equation 2 is assumed Richards' (1959) generalized growth rate function, the result is:

$$d\,BA/dt = n\,BA^{m} - k\,BA \qquad (3)$$

where:

BA = basal area

n, m, k = model parameters

This can be solved as a first-order differential equation for BA at any future time with a Bernoulli substitution (Rabenstein 1972) as follows:

$$BA_t = [n/k + (BA_0^{(1-m)} - n/k)\,e^{(m-1)kt}]^{1/(1-m)} \qquad (4)$$

where:

BA_t = basal area for any future time (t)

BA_0 = initial basal area

e = exponential function.

Comparison of equation 3 to the pinyon-juniper diameter growth data showed some benefit to slightly modifying the equation. Adding a variable for the total number of tree stems per acre (STEMS) improved basal area growth predictions.

Therefore, equations 3 and 4 were modified to include the STEMS variable. Parameters were estimated from the data (Figure 3) to obtain a prediction equation for future basal area (BA_t):

$$BA_t = [n/k + Ce^{(m-1)kt}]^{1/(1-m)} \qquad (5)$$

where:

$n = 3.5497(STEMS/1000)^{0.2591}$

$m = 0.2591$

$k = -0.0446(STEMS/1000)$

$C = BA_0^{(1-m)} - n/k$

t = time in decades

BA_0 = initial stand basal area (ft²/acre)

STEMS = total basal tree stems, 1.5 inches and larger, for all trees having at least one basal stem 3 inches or larger (number/acre).

Future basal area predictions could then be used in a stand volume equation to assess volume growth. A stand volume equation (Figure 4)

was developed from predictor variables, basal area and "site index" combined:

$$V_t = \begin{cases} 100[-0.077 + 0.398(X_t) + 0.011(X_t^2)] & \text{for } X_t \leq X_0 \\ 100[4.664 + 0.398(X_t) - 37.926/X_t] & \text{for } X_t > X_0 \end{cases} \tag{6}$$

where:

X_t = BA_t times "SITE INDEX" divided by 100

X_0 = 12

t = time in decades (the subscript t is dropped for "present time" variable definitions)

BA = basal area at DRC of all trees having at least one stem 3 inches DRC or larger (ft²/acre)

V = volume of wood and bark from stems and branches larger than 1.5 inches in diameter (ft³/acre)

"SITE INDEX" = mean height of all trees 6 inches DRC and larger with undamaged tops (ft).

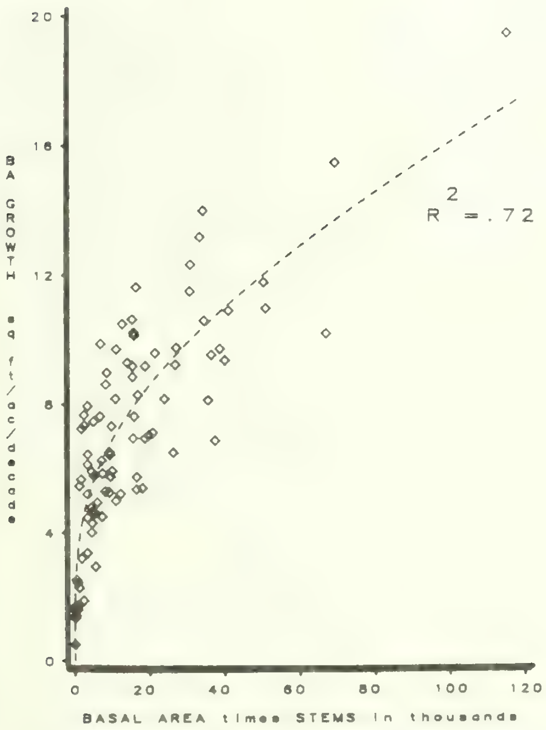

Figure 3. Basal area (BA) growth modeled (dashed line) from basal area and total basal stem data.

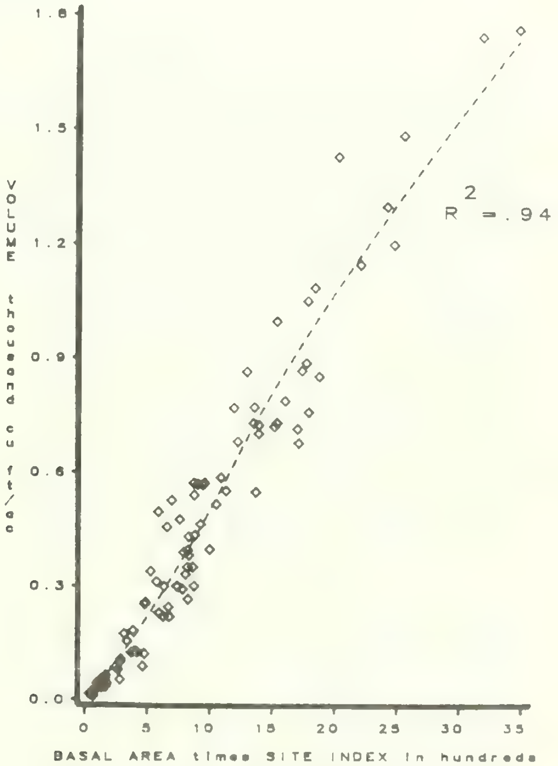

Figure 4. Volume modeled from (dashed line) basal area and "site index" data.

"Site index" was devised from the average height of all trees 6 inches DRC and larger within a plot with undamaged tops. This index seemed reasonable because heights of trees 6 to 8 inches DRC and larger, within a given plot, appeared constrained by some upper height asymptote.

Equations 5 and 6 provide volume yield for a desired projection period, but because the model was constructed from data for only a single decade, projections beyond 3 decades are not advised. Equations 5 and 6 also can provide volume growth projections. For example:

$$VG_t = V_t - V_0 \tag{7}$$

where:

VG_t = volume growth for a time period "t" (ft^3/acre)

V_t = volume yield for a time period "t" from equations 5 and 6 (ft^3/acre)

V_0 = initial volume from present basal area used in equation 6 (ft^3/acre).

DISCUSSION

Combining equations 5 and 6 can provide an assortment of volume growth and yield products for pinyon-juniper stands. However, the results should be used with full awareness of the model's limitations and underlying assumptions. Ingrowth of trees less than 3 inches DRC and mortality are not considered. The "site index" measure, average stand height of all trees 6 inches DRC and larger with undamaged tops, is assumed to remain constant. Because little site specific data drives the model, local site specific projections will probably lead to erroneous conclusions. The model is better suited for regional or Statewide projections.

Comparisons of the volume yield and growth projections to the 10-year data base (used to construct the model) showed reasonable model fit. The coefficients of determination (R^2) and variation (CV) were .70 and 35 percent, respectively, for 10-year volume growth and .93 and 22 percent for 10-year volume yield.

The results graphically showed several interesting patterns. Rate of volume yield increase over time mostly was determined by initial "site index". However, more stems per acre (more multiple-stem trees) also increased yield at a faster rate.

Periodic annual volume growth increment (PAI) averaged over a 10-year period followed some unusual response surfaces depending on the input

variables considered. For a fixed "site index" of 14 feet, an average site, PAI increased rapidly and then plateaued (Figure 5). The plateau occurred at different basal areas depending upon "site index," but in all cases the plateau corresponded to the inflection point (X_0=12) in the volume equation (eq. 6).

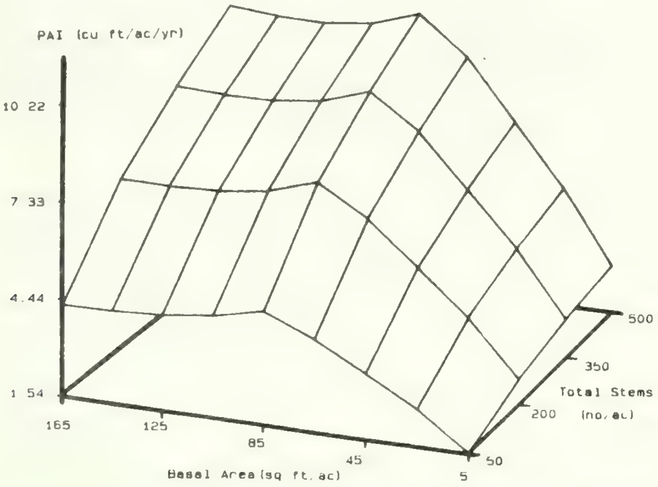

Figure 5. Periodic annual volume growth increment (PAI) for an average pinyon-juniper "site index" plateaus at a basal area of about 85 ft²/acre.

This was somewhat disturbing because the inflection point was arbitrarily placed in the volume model to obtain a sigmoidal model to fit the appearance of the volume data.

Viewing PAI with total stems per acre fixed also showed an abrupt change of slope as basal area increased. Again, this corresponded to the inflection point in the volume equation (Figure 6). It was on a

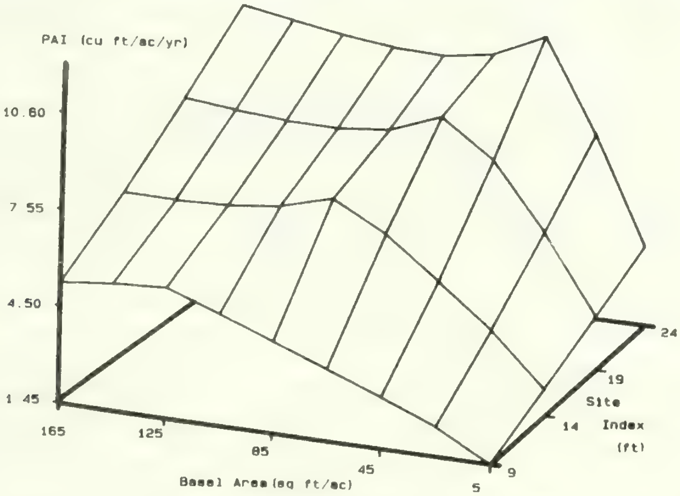

Figure 6. Periodic annual volume growth increment (PAI) for a pinyon-juniper stand, of average number of stems per acre, plateaus when basal area times "site index" equals 1,200.

diagonal this time, because the volume equation inflection point was a function of "site index."

Actual PAI results from the model (Figures 5 and 6) indicated few stands will ever exceed 10 cubic feet of volume growth per acre per year. This is probably low for pinyon-juniper woodlands as a whole. Barnes and Cunningham (1987) showed moist favorable pinyon-juniper sites offer physiological advantages to pinyon and dry harsh sites are most tolerable by juniper. Because 74 percent of the trees measured were juniper, these study data probably represented Arizona's most harsh pinyon-juniper sites.

In summary, the uneven-aged volume growth model fit the available data fairly well, but it may be of questionable value in aiding biological understanding of pinyon-juniper growth relationships. However, the model should be useful for short-term volume growth projections for areas predominately juniper.

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ESTIMATE AND TEST FREQUENCY DISTRIBUTIONS WITH THE JOHNSON S_b FUNCTION FROM STAND PARAMETERS IN YOUNG MIXED STANDS AFTER DIFFERENT THINNING TREATMENTS

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ABSTRACT The distribution of stems in diameter classes in a stand is of great importance both for the capacity of growth and yield, and the cost per cubic metre when harvested. The distribution of stems in diameter classes is influenced by the choice of thinning method. It is desirable to predict the outcome of different thinnings. Observed diameter distributions of stands of mixed Norway spruce (Picea abies (L.) Karst.) and birch (Betula pendula Roth and Betula pubescens Ehrh.) are adapted to the Johnson S_b probability function. Goodness of fit between observed and calculated frequencies was measured with the one-sided Kolmogorov-Smirnov statistics. All distributions fit at the alpha = 0.05 level of significance. The Johnson S_b parameters are transformed to four fractiles. The fractiles are predicted with multiple regression and two multivariate techniques. The independent variables are characteristics of site and stand. To use multivariate analyses when predicting the probability density function gives acceptable prognoses for practical applications even if the methods can not always predict the lower diameter classes correctly. The model can be used in young unthinned mixed stands of Norway spruce and birch, and cover the geographical area of South and Middle Sweden.

INTRODUCTION

The distribution of stems in diameter classes in a stand is of great importance both for the capacity of growth and yield, and the cost per cubic metre when harvested (Cao et al, 1982). The distribution of stems in diameter classes is influenced by the thinning method. It is also desirable to predict the outcome of different thinnings. In Norway spruce (Picea abies (L.) Karst.) regenerations it is common with a natural regeneration of birch (Betula pendula Roth and Betula pubescens Ehrh.). In such stands there is a silvicultural choice between cleaning and an early whole tree birch thinning. After thinning the diameter distribution of the remaining trees can be used as component of an individual tree growth model. Together with average tree volume per diameter class, the diameter distribution model of removed trees will make it possible to determine the merchantable volume out of total volume before thinning. In stands of young uncleaned mixed Norway spruce and birch an experiment with three thinning methods was performed (Figure 1).

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Figure 1. The thinning methods in mixed stands of Norway spruce and birch.

Adaptation of diameter distributions to the unthinned stands is discussed by Tham (1987b). The adaptation is made for the stand as a whole, as well as for Norway spruce and birch separately. These functions can also be used when all birches are felled. The distributions of remaining and removed trees in a stand thinned in strips are assumed to be the distributions of the thinned stand divided by two.

The aim of this work is to predict and test diameter distributions in mixed stands of Norway spruce and birch where the birches are thinned to a shelter, both for remaining and removed trees. The prediction equations in earlier work, together with the prediction equations in the present work will make it possible to estimate diameter distribution after different thinning methods in young unthinned mixed stands of Norway spruce and birch.

MATERIAL AND METHODS

The data for this study come from mixed Norway spruce and birch stands. Altogher 21 stands were studied in South and Middle Sweden. The experimental design, initial position and detailed description of data collected were reported by Tham (1987a).

In the present work, the Johnson S_b distribution (Johnson, 1949; Johnson & Kotz, 1970) is chosen as a diameter distribution because of its flexibility and capacity to fit a broad spectrum of shapes (Hafley & Schreuder, 1977). In the Johnson S_b function the parameters psi and lambda are location and scale parameters, whereas delta and gamma determine the shape of the distribution. When the value of delta increases the shape implies a greater excess. An increasing absolute value of gamma implies more skewness.

Estimation of the parameters is done according to Mønness (1982; pers. comm.), with maximum likelihood estimation. Goodness of fit between observed and calculated frequencies was measured with the one-sided Kolmogorov-Smirnov=(KS) statistics. The Johnson S_b distributions are tested at the alfa = 0.05 level of significance. Instead of the relation between Johnson S_b parameters and stand characteristics, Mønness (1982) sought the relation between fractiles and stand characteristics. A fractile is a real number (diameter) such as a certain amount of trees having a diameter less than or equal to that number. The chosen fractiles are; alfa=0, alfa=0.3085, alfa=0.5 and alfa=0.6914. When the diameter distributions are predicted from

the stand characteristics the fractiles must be solved to obtain the Johnson S_b parameters. The fractiles (as well as the Johnson S_b parameters) are dependent on each other. The recognition of a systematic pattern of the four fractiles makes it desirable to use multivariate techniques. In this work, multiple regression, simultaneous equation models (multivariate regression) and partial least squares (PLS) modelling with latent variables are used to estimate the relation between fractiles and site and stand characteristics. The model uses the characteristics; mean diameter, mean diameter of the dominant trees, basal area, number of trees, latitude, site index, age and dominant height.

Simultaneous equation models (here abbreviated to SEM) are computed using the Lisrel VI package (Jöreskog & Sörbom, 1984).

The partial least squares modelling with latent variables in the twoblock predictive form (here abbreviated to PLS2) is designed to extract and model regularities in multivariate data which have predictive relevance. In latent variable models the basic assumption is that each x-variable contains an unknown part that is correlated to an unknown part of the y-variables. Conceptually, this is formulated as if the y-variables are influenced by a number of factors, latent variables (Dunn et al., 1984). The PLS2 model is computed with the SIMCA-3 package.

To check the prediction power of the three different methods the stands were divided in estimation and prediction sets. The estimation set is made by randomly excluding three objects. This is repeated seven times to get an estimation set for each object. The objects are then tested with observed towards predicted diameter distribution. As measure of goodness of fit the KS test is applied as follows. The limit KS value (alpha = 0.05) for each object is calculated and divided by the actual KS limit value (Tham, 1987b).

$$\frac{\text{Actual KS value}}{\text{Limit KS value}} = \text{KS-quotient}$$

RESULTS

Table 1. Values of Johnson S_b parameters and fractiles of mixed stands of Norway spruce and birch.

	Remaining trees min	Remaining trees max	Removed trees min	Removed trees max
psi	-1.52	-0.20	-1.53	0.38
lambda	13.29	691.54	9.11	39.52
delta	0.89	1.41	0.84	2.27
gamma	0.45	7.61	0.44	3.27
D_0	-1.52	-0.20	-1.53	0.38
$D_{0.3085}$	1.41	4.35	1.17	5.67
$D_{0.5}$	2.13	7.16	1.94	7.38
$D_{0.6914}$	3.14	10.54	3.01	9.42

The Johnson S_b parameters and the fractiles are estimated for remaining and removed trees (Table 1).

All distributions both for remaining and removed trees passed the one-sided KS test at alpha = 0.05 level of significance. Prediction equations for D (alpha=0), D (alpha=0.3085), D (alpha=0.5), and D (alpha=0.6914) together with independent variables form a Johnson S_b diameter distribution model. Prediction equations for multiple regression and SEM are given in Table 2.

Table 2. Regression coefficients, standard error and squared multiple correlation coefficients.

	D0 coeff.	D0 s.e.	D0.3085 coeff.	D0.3085 s.e.	D0.5 coeff.	D0.5 s.e.	D0.6914 coeff.	D0.6914 s.e.
Remaining trees, simultaneous equation models (SEM)								
lnDGG	-	-	-	-	-	-	1.487	0.656
DGGlnNG	-	-	-	-	-	-	0.012	0.003
ln DGS	-	-	-	-	-	-	-1.775	0.701
$D_{0.3085}$	0.454	0.121	-	-	-	-	-	-
$D_{0.5}$	-	-	1.392	0.083	-	-	-	-
$D_{0.6914}$	-0.309	0.055	-0.515	0.057	0.694	0.008	-	-
Remaining trees, multiple regression (MR)								
DGG	-0.012	0.001	0.053	0.002	0.082	0.003	0.118	0.003
Removed trees, simultaneous equation models (SEM)								
DGBlnNB	-	-	-	-	-	-	0.011	0.000
$D_{0.3085}$	0.477	0.131	-	-	-	-	-	-
$D_{0.6914}$	-0.286	0.069	0.521	0.020	0.739	0.011	-	-
Removed trees, multiple regression (MR)								
DGB	-0.004	0.001	0.048	0.003	0.069	0.002	0.093	0.002
Squared multiple correlation coefficient (R^2)								
Remaining trees								
SEM	0.954		0.999		0.998		0.985	
MR	0.906		0.972		0.983		0.988	
Removed trees								
SEM	0.564		0.974		0.996		0.992	
MR	0.294		0.957		0.983		0.991	

Key to letter groupings

ln = Natural logarithm
DGG = Diameter corresponding to mean basal area, on bark, Norway spruce, cm
NG = Number of stems, Norway spruce/ha
DGS = Diameter corresponding to mean basal area, on bark, dominant trees, cm
DGB = Diameter corresponding to mean basal area, on bark, birch, cm
NB = Number of stems, birch/ha

Squared multiple correlation coefficients (R^2) show that the mean diameter is well correlated to the different fractile values. The interrelation between the dependent variables makes the (R^2) slightly higher when SEM is used instead of multiple regression. PLS2 of remaining trees reached a total of four significant terms. Removed trees gave seven significant terms. The latent variables are described by scaled weights, averages, loadings and loading weights. The latent variables, together with the dependent variables, form a Johnson S_b diameter distribution model. The KS quotients from the three methods are plotted against each other (Figure 2).

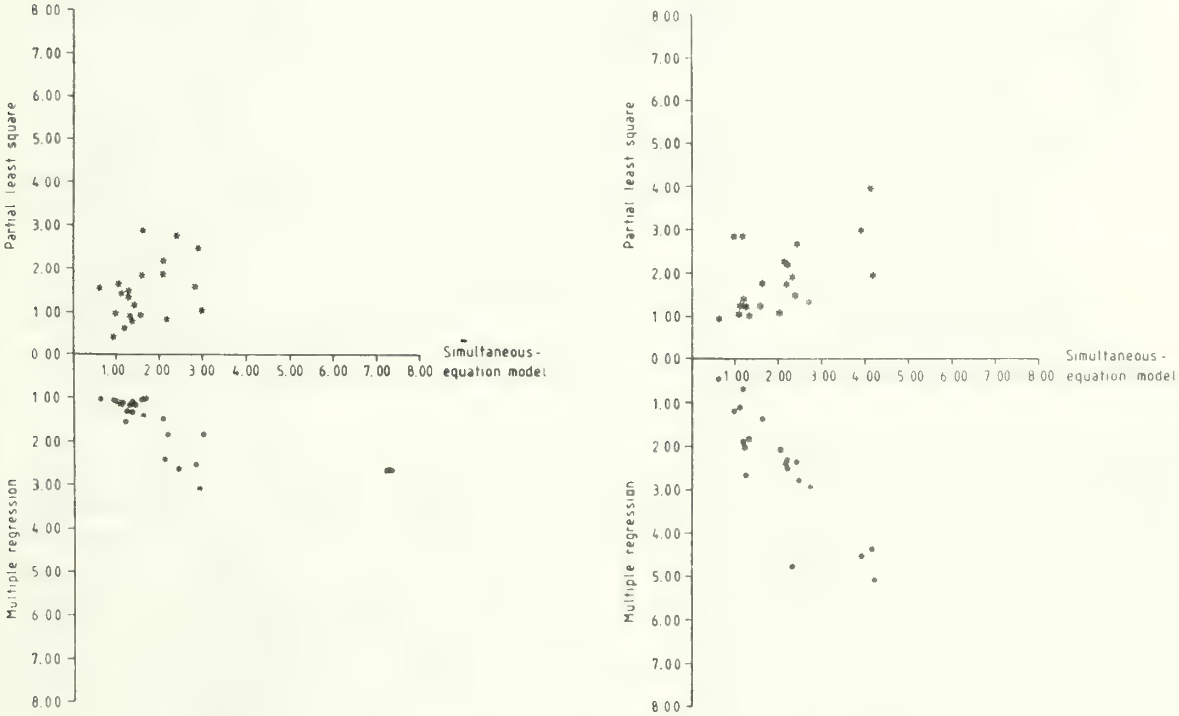


Figure 2. Kolmogorov-Smirnov quotients, a comparison between multiple regression, simultaneous-equation model and partial least squares. Remaining and removed trees in mixed stands of Norway spruce and birch.

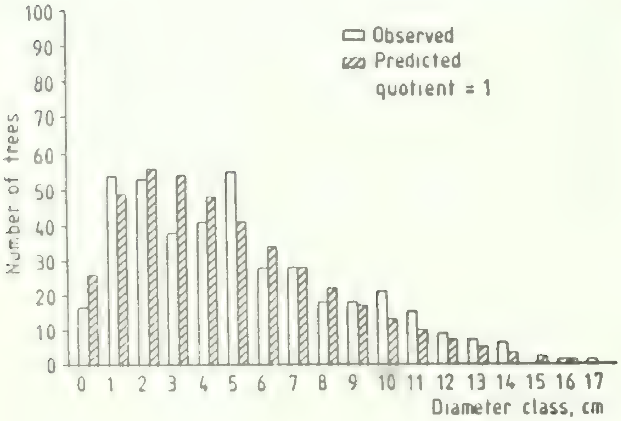
The maximum KS-quotients for remaining trees are 3.12 (MR), 2.96 (SEM) and 2.85 (PLS). The maximum KS-quotients for removed trees are 5.08 (MR), 4.17 (SEM) and 3.90 (PLS). A comparison of KS-quotients between methods, observation by observation, resulted in SEM beeing better than multiple regression in 11 cases of 21 for remaining trees and 17 for removed. PLS2 were better than SEM in 12 cases of 21, both for remaining trees and removed trees.

DISCUSSION

Mixed stands which have irregular distributions need a model formed from different segments of cumulative distribution functions (Cao & Burkhart, 1984). The Johnson S_b function, however, is flexible enough to fit young shelter thinned stands of mixed Norway spruce and birch.

There are different numbers of stand characteristics used in the different prediction techniques. In multiple regression only mean diameters are used. If more stand characteristics (or others) are used it would in this case be impossible to solve the Johnson S_b parameters from the predicted fractile values. In simultaneous equation models stand characteristics such as number of stems and mean diameter are included. The partial least square model also uses dominant height, basal area and site characteristics as altitude, site index and latitude. All characteristics can be determined before thinning. Mønness (1982) tried to find a relation directly between the Johnson S_b parameters and stand characteristics, but the model gave a very poor fit. With multivariate techniques it might be possible to find these relations. This is not attempted in this study but in further work this should be considered.

When the explanation degree in the stand characteristics is diluted, there is a need for many stand characteristics to explain the variation in fractile values. In such cases the partial least square method has an advantage.



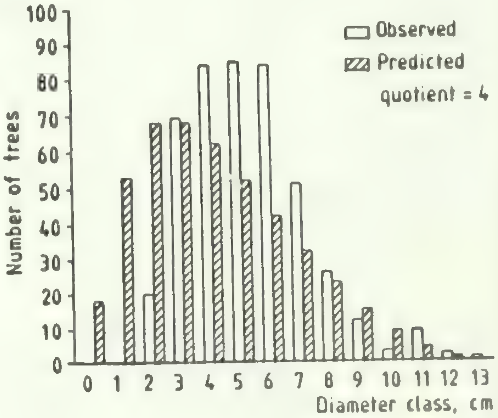


Figure 3. Comparison between observed and predicted diameter distributions at different Kolmogorov-Smirnov quotients.

When the K-S quotient are four , or above, the observed and predicted distributions do not have their maximum value in the same diameter class.

The results in this study all trees above breast height are predicted. There is no minimum dimension. This, together with the fact that the maximum value of the KS-quotient almost always occurs in the first two diameter classes, makes it difficult to compare with other studies.

The simultaneous equation model and partial least square method can be used and gives an acceptable prognosis when predicting diameter distributions in young mixed stands of Norway spruce and birch. All K-S quotients for the partial least square method are beneath three and for the simultaneous equation model there are three observations above. My conclusion is that these methods give rise to useful practical predictions even if the lower diameter classes are not always correctly estimated. It covers the geographical area of South and Middle Sweden.

An example of application is given in Table 3.

Table 3. Basal area, m^2/plot, of remaining and removed trees after the three different thinning methods. Simultaneous equation models, obs=observed values, pre=predicted values.

	Birch thinning		Shelter thinning		Line thinning	
	obs	pre	obs	pre	obs	pre
Remaining trees	0.67	0.43	1.25	0.63	1.34	1.16
quotient	3.3		2.8		2.8	
Removed trees	1.98	1.97	1.40	1.16	1.34	1.16
quotient	1.1		2.0		2.8	

The K-S test recognizes the maximum cumulative difference between the two distributions. If the quotient is beneath 2.5 the basal area calculated from observed and predicted distributions will show small differences. When estimating the parameters the predicted and observed distributions will not have the same basal area. If the parameters are recovered instead of estimated the mean diameter will be equal in both cases (Burk & Newberry, 1984; Eriksson & Salnäs, 1987). It is, however, only possible when the Weibull distribution is used. If the Weibull distribution function is flexible enough to fit mixed stands of Norway spruce and birch is not tried in this study.

ACKNOWLEDGEMENTS

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USER FRIENDLY APPLICATIONS OF THE FORCYTE ECOSYSTEM MODEL ON A MICROCOMPUTER

M.J. Apps[1], W.A. Kurz[2], J.P. Kimmins[2] and K.A. Scoullar[3]

ABSTRACT. The ecosystem model FORCYTE-11 has been transferred successfully from a mainframe environment to microcomputers equipped with a 32-bit coprocessor board. A user friendly software package, PROBE, was developed to facilitate the preparation, execution and analysis of multiple runs of simulation models for applications such as sensitivity analysis and management gaming. PROBE was used to conduct preliminary sensitivity analysis of FORCYTE-11.

INTRODUCTION

Until recently, large computer simulation models have been restricted to high speed, large memory, mainframe computers. New advances in microcomputer technology have changed this situation. The advent of the faster 32-bit microprocessor, the removal of the 640 kilobyte memory limitation, and the development of microcomputer compilers capable of processing very large programs in commonly used languages such as FORTRAN have made the economical desktop computer a suitable environment for large models. Utilization of the full computational power of this new generation of desktop computers may be enhanced by the development of user-oriented supervisory software to facilitate multiple runs and analysis of the large output data sets that are produced. Such software can also partly automate the otherwise time consuming and tedious job of conducting sensitivity analysis on large, complex models.

In this paper we describe the successful transfer of FORCYTE-11 (Kimmins et al., this volume) from the University of BC mainframe (Amdahl 580) to a PC, and the subsequent development of a user friendly software package (PROBE) to permit the preparation, execution and analysis of multiple runs of FORCYTE for activities such as management gaming and sensitivity analysis. Originally conceived to assist in probing the sensitivity of FORCYTE to various input parameters, PROBE has much wider applicability and can be used to enhance the model's use in basic research, teaching, and as a predictive forest management tool. A simple example will be used to illustrate PROBE's application in sensitivity analysis of the model.

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FORCYTE

The philosophy and approach of FORCYTE-11 are presented elsewhere in these proceedings, and only a few relevant points will be repeated here. FORCYTE-11 presently consists of three separate FORTRAN programs (FORSOILS, TREEGROW and MANAFOR), each containing several thousand lines of source code (additional modules are in preparation for the simulation of shrubs, herbs and mosses).

The FORCYTE modules FORSOILS and TREEGROW define and describe various aspects of a forest ecosystem and make this information available to the MANAFOR module, a program which provides a simulation of user-specified management strategies for this ecosystem. These three FORCYTE modules are typically executed in sequence, and each requires a user-prepared input data file. MANAFOR also requires binary input files (TREND-files), which are generated by the other two modules. Once the appropriate TREND files have been established, any number of runs of the MANAFOR module can be executed without repeating the runs of the preceeding modules.

Each FORCYTE module can produce large quantities of diagnostic output which can be reviewed by the user. Prior to the development of PROBE, each run of each module was treated as a separate entity requiring editing of the input data files and execution of the program module by the user. Direct comparison of the results of a series of runs was performed by manually extracting the results of interest from the various output files.

THE HARDWARE

The personal computers used in this project (IBM PC/XT/AT and compatibles) are equipped with a 32-bit coprocessor board (DEFINICON DSI-32) with its own on-board RAM memory. The execution of FORCYTE-11 requires at least 2 Mb of RAM. In the FORTRAN source code only the filename declarations had to be modified to permit the successful compilation of the programs with a FORTRAN 77 compiler available for the DSI coprocessor board.

The coprocessor board, with a 12.5 MHz clockspeed (faster ones are now available), executes an 80-year simulation with MANAFOR in approximately 2 to 4 minutes. The time varies with the input/output facilities of the PC (i.e. availability of a RAM disk and the speed of the harddisk).

In operation, the coprocessor board provides an entirely separate and independent background computing environment within the PC. Several PC software packages are available to provide a foreground/background operation in which the DSI coprocessor can be executing one task in the background while the PC is being actively used in the foreground for some other task. The PROBE user can exploit this feature by conducting a series of FORCYTE runs on the coprocessor board, while concurrently planning the next series or analyzing a previous one in the PC foreground.

PROBE

PROBE consists of several programs and files which assist the user in preparing, executing and analyzing multiple runs of a simulation model. Primary objectives in the development of PROBE were to permit the unattended execution of large numbers of runs and to facilitate comparison of the results of such runs.

Although developed for FORCYTE, PROBE in its generic form can be used with any simulation model which can be controlled from the PC or MS-DOS environment. In addition, although currently using the DSI coprocessor board, it can be used to control programs executing in the DOS environment (e.g. the DOS version of FORCYTE-10). This may be of increasing importance as new operating systems and faster CPUs become available for personal computer systems.

PREPARATION OF MULTIPLE RUNS

PROBE gives the user full control over the sequence in which the different FORCYTE modules will be executed and over the input data that are used for these runs. To achieve this flexibility, the user constructs a simple sequence file which PROBE uses to determine the order of execution and the data files to be used. Each element of the sequence consists of the FORCYTE module name and the data case number. For example, a user might run FORSOILS and TREEGROW to initialize the simulation of a particular ecosystem, and then apply different management regimes, such as a series of different levels of thinning, to this ecosystem. The sequence "S1 T1 M1 M2 M3 M4" signals the execution of FORSOILS and TREEGROW with a particular set of data in the SOILDATA (case 1) and TREEDATA (case 1) input files, followed by four successive runs of MANAFOR for the different thinning levels defined in MANADATA (cases 1 through 4). All four MANAFOR runs use the same TREND curves generated by S1 and T1.

Each FORCYTE module case run requires a separate input data file describing that case. Because successive cases often differ only in a few data, PROBE uses a data overlay technique so that only one default data set is maintained for each module. Case changes are stored in separate files which the user prepares with the assistance of an interactive PROBE utility program. This program also reduces the risk of operator-introduced structural changes to the input data file.

Sequences of virtually any length and complexity can be constructed by the user. Figure (1) illustrates a sequence in which the four MANAFOR treatments are run following each of two separate cases of TREEDATA. Such a sequence is the first step in performing a sensitivity analysis for the model, as discussed below.

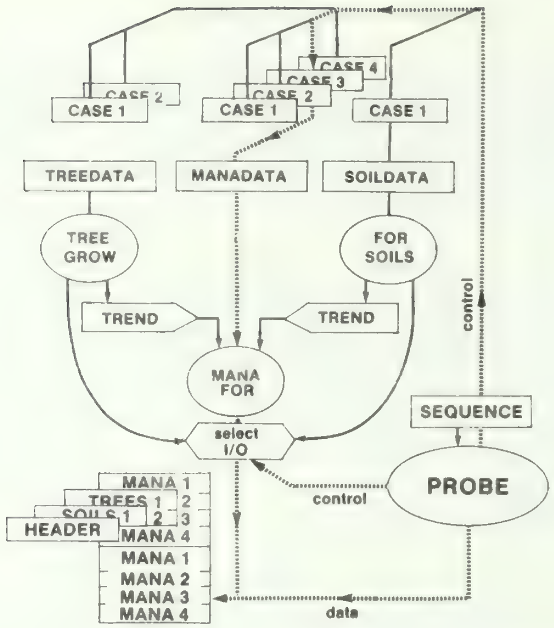

Figure 1. PROBE supervises the execution of multiple runs of the FORCYTE modules FORSOILS, TREEGROW, and MANAFOR. In this example, case 3 of MANADATA (dotted line) is prepared by PROBE. MANAFOR is then executed, and the selected results are added to the output file which contains the previous cases' results.

PROBE EXECUTION AND OUTPUT

A complex batch program controls the case overlay of data files, orders the FORCYTE module execution according to the user-specified sequence, and performs certain error-checking functions to ensure the proper execution of the modules which were called. It also redirects the selected FORCYTE module output to an output file which provides a complete record of the PROBE run. As schematically indicated in Figure 1, the FORCYTE data output for each case is saved and ordered in blocks for each of the modules executed. Only a subset of the potentially available FORCYTE output information is retained by PROBE. However, each case record includes sufficient data to exactly repeat the simulation if more detail is needed at a later time.

To provide for long unattended (overnight or background) execution, PROBE uses the special sequence "Hn" to allow the user to specify a new output file and to preface it with a descriptive header block. Using a new header for each, a series of computer experiments can be preconstructed and set into operation for overnight or background execution. A PROBE utility automatically archives the results of the experiments in successive files PROBEOUT.n (n = 0, 1, 2,...). There is no theoretical limit to the number of runs that can be executed in one session, although the amount of storage space available to archive the result files will act as practical limit.

ANALYSIS OF MULTIPLE RUNS

The output file contains two types of variables: dynamic and static. The status of dynamic variables (e.g. annual stemwood biomass) is written to the output file at user-specified time intervals. The status of static variables is reported for a particular time (eg. stemwood biomass at harvest) or for a time average (eg. mean annual increment over a rotation).

PROBE's output file is structured to facilitate its transfer into a spreadsheet. In addition to the functions normally performed by common spreadsheet programs (such as SYMPHONY TM), several menu-driven routines have been developed for use with SYMPHONY. These assist in the analysis and interpretation of both static and dynamic variables. Options presently available include the automated importation of PROBE result files, the compilation of summary tables and the graphical display of both dynamic and static variables.

In addition, a special routine has been developed to extract 2 way variation tables in which a user-chosen output variable is tabulated for the different management treatments (e.g. MANADATA cases representing various management regimes) and for different input parameter values (eg. TREEDATA cases using different values of ecosystem parameters). These tables provide the starting point for a specialized form of sensitivity analysis, a simple example of which is given below.

THE USE OF PROBE WITH FORCYTE-11: SENSITIVITY ANALYSIS

The objectives of sensitivity analysis must be clearly distinguished from those of model validation. While validation attempts to verify that the simulation results are close to or identical with the "real" observed values, sensitivity analysis investigates the model's response to changes in the input parameters. A review of the various approaches to and applications of sensitivity analysis is beyond the scope of this paper.

Sensitivity analysis of a model is typically performed to investigate the question "How do selected output parameters respond to changes in selected input parameters?" PROBE permits us, however, to take the next step and ask "how are the comparative predictions for a series of management strategies affected by these input parameter variations?" This question requires the assessment of the model's response to changes of parameters along two axes: the varied input parameter axis and the management treatment axis.

To illustrate the use of PROBE for such a second order sensitivity analysis we considered a relatively simple example. We chose five levels of a single input parameter which describes the light level below the canopy at the maximum overstory foliage biomass level of the stand. The five levels are the default value (15% of the light level above the canopy) multiplied by 0.5, 0.9, 1.0, 1.1, and 2.0 for cases 1 through 5 of TREEDATA, respectively. For each of the 5 runs of TREEGROW, four different management regimes were simulated. These describe four levels

of thinning intensity in which 0%, 20% 40% and 80% of the stemwood biomass are removed at age 20 for cases 1 through 4, respectively.

Five runs of TREEGROW and twenty runs of MANAFOR were executed with PROBE to obtain the results for this example. The results were then analyzed using the spreadsheet routines developed for use with PROBE. As a demonstration only, Figure 2 shows the results for stemwood mean annual increment (per ha) at the end of each of the twenty runs.

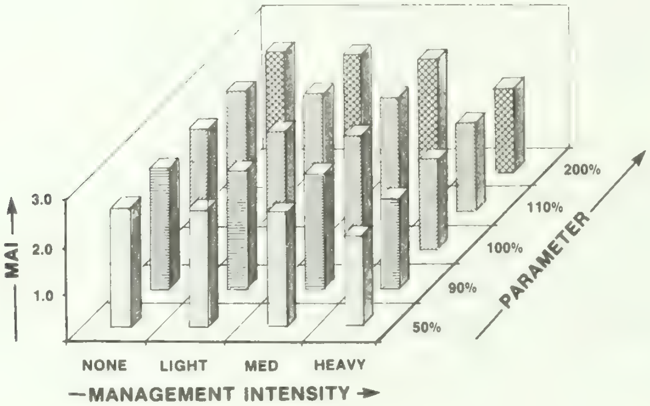

Figure 2. Stemwood mean annual increment (MAI) at the end of an 80-year rotation in a hypothetical aspen ecosystem. Each of the twenty bars represents the result obtained for a particular combination of thinning intensity and input parameter value.

As anticipated, the mean annual increment of the stand declined with increasing thinning intensity. Variations of the input parameter had little effect on MAI with no thinning and light thinning (maximum deviation from the default value was 0.3%, Figure 3). In the heavy thinning regime, differences in the output variable due to variations of the input variable were more pronounced and reached a maximum deviation from the default value of -4.3%. A full explanation of the different simulated processes which were affected by the changes to the input parameter is beyond the scope of this paper.

The above example illustrates the importance of conducting sensitivity analyses of a complex model by varying both the input parameters and the processes simulated with those input data. Although there was no effect of the variation of the input parameter at one management regime, at another regime the differences could be important. Such an application-oriented sensitivity analysis is particularly important with models, such as FORCYTE, which attempt to make management predictions.

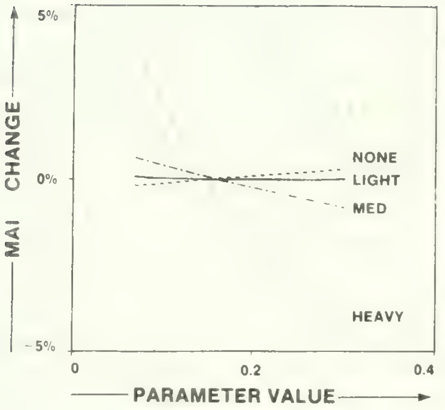

Figure 3. The data of Figure 2 expressed as percent deviation from the result obtained for the default input parameter.

Using PROBE, such an analysis can be prepared, excecuted and analysed efficiently. Compilation of the resulting graphs and tables will give future users of FORCYTE an indication of its sensitivity to changes in input parameters.

Future research plans include a systematic investigation of the model's response to variations in different input parameters using the approach outlined in this paper. The model's input data can then be classified into broad classes of sensitivity which can be used in deciding on the required levels of accuracy of the input data.

CONCLUSIONS

The transfer of FORCYTE-11 to a microcomputer equipped with a special coprocessor board has made the model available to users without access to mainframe computing facilities. The personal computer environment provided opportunities for the development of user friendly software which can enhance the utility of FORCYTE. The underlying concept and the software of PROBE, which were originally developed for FORCYTE, can be applied to other simulation models on personal computers. Sensitivity analysis, management gaming and other applications which require repeated runs of the same model can be performed with PROBE.

The example of the application of PROBE to preliminary sensitivity analysis of FORCYTE-11 emphasizes the need to conduct second order sensitivity analysis, in which the model's input parameters are varied, and a range of management scenarios are simulated with each of the varied input parameters.

A TREE GROWTH MODEL WITH MULTIPLE STRESSES

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ABSTRACT. A literature review of plant models for crops and forest trees was made. The models were either not physiologically based or were incomplete, too detailed on some processes but lacking in others. No model was capable of simulating tree responses to multiple stresses. A new generation tree model was formulated. The model incorporates subroutines from an existing model (ILWAS) to calculate daily soil temperature, soil moisture, cations (including aluminum species) and anion concentrations in the soil solution at the root zone. A plant module is added to simulate the daily tree life (growth physiology), subjected to the dynamic impacts of air pollution (ozone and acid deposition), aluminum toxicity, and drought (stress physiology). The model is currently under development and testing. It will be used to design research to collect necessary data in the laboratory and in the field. Model coefficients will be calibrated with data from exposure experiments where environmental conditions are controlled. The model can then be extended to the field where environmental conditions change dynamically.

INTRODUCTION

An environmental concern of air pollution, including acid deposition, is its potential effects on tree vigor and forest decline. This concern was kindled by the large scale dieback and mortality of Norway spruce and fir observed in the forests of West Germany and the dieback of red spruce observed in the White Mountains, Green Mountains, Adirondack Mountains and Great Smoky Mountains of the United States (Johnson and Siccama, 1983 and EPRI, 1985).

Both natural and man-made factors could have caused the forest decline. Ulrich and his colleaques advanced the aluminum toxicity hypothesis (Ulrich, Mayer, and Khanna, 1980). According to this hypothesis, acid deposition acidifies the soil and transforms the ubiquitous aluminum into its toxic forms. This toxic aluminum weakens fine roots and kills trees. However, other German researchers (e.g. Bauch and Rehfuess according to Jonhson and Siccama (1983)) attributed the cause of dieback to calcium deficiency, ozone concentration, acid mist and climate factors (drought and frost). Based on the review of scientific evidence available in the literature, Hakkarinen and Allan (1986) and EPRI (1985) concluded that various combinations of environmental stresses controlled the health of a forest.

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When multiple factors are involved, it becomes difficult to analyze the cause-effect relationship by conventional statistical procedures. In nature, one factor may have a positive impact on growth, while another factor neutralizes its effect. A chemical factor can be stimulatory at low concentration and become toxic at high concentration (Chen and Goldstein, 1985). Since environmental factors can vary with time, a factor can be stimulatory for growth at one time and be toxic for stress at the other.

This paper describes a research project to develop a model that can perform the real time simulation of a tree life, integrating the stimulatory and toxic effects of multiple factors including air pollution and natural environmental parameters (e.g. temperature, moisture and nutrients). The project began with a review of previous plant (crop and tree) models and the formulation of a physiologically based single tree model. The model is under development and is used to specify the required data which will be collected by complementary research projects. Upon calibration, the model will provide a theoretical framework to understand how and why a tree is dying (or surviving) and how and why a forest is declining (or not declining) from stresses caused by air pollution and acid deposition.

MODEL REVIEW

Crop models for corn, soybean, sugar beet, and red radish were reviewed. Tree models are of two types: forest management models and successional models. The study reviewed 6 distance-dependent and 3 distance-independent forest management models. Successional models included JOBOWA (Botkin, Janak, and Wallis, 1972) and its derivatives FORET (Shugart, McLauglin, and West, 1980) and SILVA (Kercher, Axelrod and Bingham, 1980). The CERES model described by Dixon, Luxmoore, and Begovich (1976) was also reviewed.

Plant models were analyzed for their assumptions, formulations, inputs, outputs, calibrations, and verifications. Results were reported by Chen (1987). Generally, the formulations of crop models include diffusion of carbon dioxide through stomata, light attenuation through leaves, photosynthesis of carbohydrate, chemical synthesis of organics, material transport between plant parts and production of harvestable dry matter. Effect of water status on photosynthesis is included in some models. With a time step of 15 minutes to an hour and a total simulation period of 100 to 150 days, crop models tends to be very detailed with many speculative assumptions.

Forest management models use regression equations to calculate annual growth as a function of diameter at breast height and site index. These models do not incorporate plant physiology or environmental factors. As such, they cannot simulate the physiological effects of air pollution and drought.

Successional models are based on presumed rules of species competition in a forest stand. The competition rules are arbitrary and cannot be verified. Models of this type have limited utility in the study of pollution impacts. They cannot evaluate how and why a forest is (or is not) "dying". Nor can they determine the level of forest damage caused by individual and combined stresses. They can evaluate successional changes of tree species, after the air pollution effect on growth reduction and mortality increase are known. Even then, the successional response can simply be a mathematical fiction due to its unverifiable nature.

Many models start with "transport", e.g. diffusion of carbon dioxide from air to stomata, diffusion of water from soil to root, diffusion of water from root to canopy, diffusion of photosynthate from canopy to plant parts and so on. This approach leads to the use of "resistor" analogy. However, concentration gradients and resistances used in the transport equation are rarely measured. The transport calculations are often based on a shaky ground. Furthermore, a living tree has an agenda of its own. A tree can use energy to transport material against a concentration gradient.

Among all the models reviewed, no model could simulate tree responses to the combined stresses of ozone, acid deposition, aluminum toxicity and drought.

MODEL FORMULATIONS

The model under development is designed to simulate a single tree (Figure 1). The single tree may be surrounded by neighboring trees. A percent shading factor defines the light fraction absorbed by neighboring trees. Within the root zone, there are roots of neighboring trees. A percent sharing factor accounts for their water and nutrient uptake.

State variables for the tree are organized at the whole plant level, i.e. canopy, stem, and root. The canopy has a mass, a leaf area and age classes of leaves. The stem (which includes branches) has a mass, a height, and a diameter at breast height. The mass of the stem is divided into heartwood and sapwood. The root has two classes (coarse and fine) and is distributed among soil horizons. All the masses of canopy, stem, and root have their stoichiometric contents of water and nutrients (Ca, Mg, K, C, N, P and etc.). The soil is divided into horizons. Each horizon has its mineral composition (including organic matter) and soil solution chemistry.

The model is driven by the daily values of maximum and minimum air temperatures, wet bulb temperatures (or relative humidity), precipitation, precipitation chemistry, solar radiation, and maximum ozone concentration. The model accepts the daily meteorological and air pollution data and simulates the changes in state variables for the soil and tree.

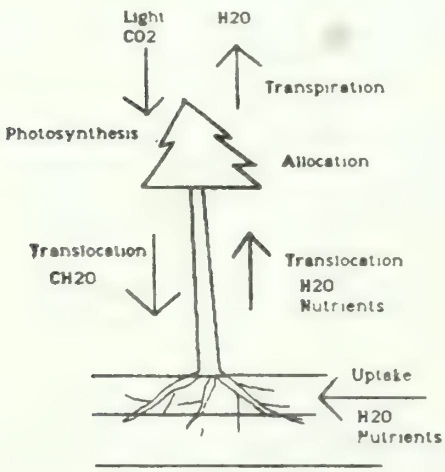

Figure 1. The Air-Plant-Soil System

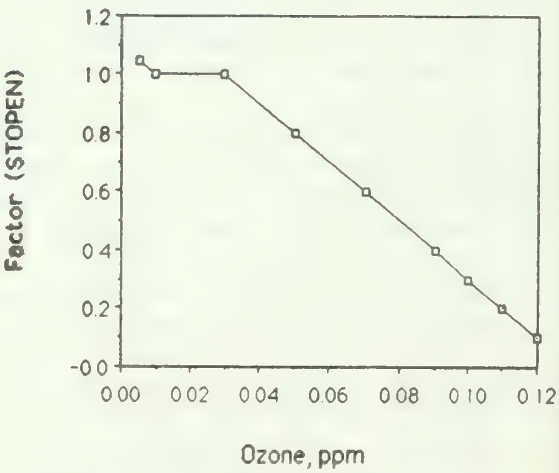

Figure 2. A Hypothetical Dose-Response Function

The model is based on the genetic blueprint of a tree. The genetic blueprint specifies how the tree grows under non-stressful conditions. This growth is then modulated by stressful conditions in the air and the soil. With this procedure, the model eliminates the need for transport equations. The allocation of photosynthate to grow plant parts is implicitly defined by allometric relationships.

Preliminary model formulations have been described by Chen and Gomez (1987). A brief discussion of equations related to allometry, phototsynthesis, respiration, nutrient uptake, phenology, growth and mortality of plant parts, and sublethal and lethal effects of air pollution will be presented here.

The model scales each plant part to the diameter at breast height (DBH). Thus, the potential canopy size is related to DBH as follow:

$$PCANOPY = a\,(DBH)^{b} \qquad (1)$$

where PCANOPY = potential canopy mass in gram, DBH = diameter at the breast height in centimeter, and a and b = coefficients.

The canopy of a tree has a unique shape and light extinction property,

$$E = a\,(LA) \qquad (2)$$

where E = whole canopy light extinction coefficient in percent of light per canopy leaf area, LA = whole canopy leaf area, and a = coefficient.

The amount of light intercepted by the canopy is,

$$Ii = Io\,[1 - \exp(-\,a\,LA)] \qquad (3)$$

where Ii = amount of light intercepted by the canopy in calorie per hour, Io = light intensity above the canopy after accounting for light interception by neighboring trees, LA = whole canopy leaf area, and a = coefficient. This calculation is performed hourly and integrated to the daily value (Id).

The daily sugar production is calculated by,

$$CPHOTO = (EEF)\,(Id)\,(STOPEN)\,\theta^{(T-20)} \qquad (4)$$

where CPHOTO = sugar production for the day in milligram carbon per day, Id = light interception for the day in calorie per day, EEF = a constant for the energy use efficiency (approximately 5 microgram C per calorie of energy), STOPEN = an index of stomatal opening, θ = a temperature coefficient, and T = air temperature in degree Celsius.

The model accounts for maintenance and growth respiration. Maintenance respiration is assumed proportional to the living biomass of the tree,

$$RESPM = Kr\,(LB)\,\theta^{(T-20)} \qquad (5)$$

where RESP = maintenance respiration in carbon equivalent of sugar, Kr = maintenance respiration constant at 20 degree Celsius, LB = total living biomass of canopy, root, and stem (excluding heartwood), and θ = a temperature coefficient.

The growth respiration is made proportional to the amount of growth,

$$RESPG = (G/Y) - G \tag{6}$$

where RESPG = growth respiration, G = total growth in canopy, root, and stem, and Y = yield coefficient, i.e., the amount of carbon incorporated into biomass per unit of carbon used to create the biomass.

Photosynthesis less respiration is net photosynthesis,

$$NET = CPHOTO - RESPM - RESPG \tag{7}$$

where NET = net photosynthesis in carbon unit, CPHOTO = photosynthesis in carbon unit, RESPM = maintenance respiration in carbon unit, and RESPG = growth respiration in carbon unit.

Net photosynthesis creates a demand for nutrient to maintain stoichiometry. For example, the nutrient demand for nitrogen is,

$$DN = 1.01\ (NET)\ (Ns/Cs) + (Ns - N)\ (POOL) \tag{8}$$

where DN = nutrient demand for nitrogen, NET = net photosynthesis in carbon unit, Ns = stoichiometry of nitrogen in biomass, Cs = stoichiometry of carbon in biomass, N = actual nitrogen concentration in the storage pool, and POOL = biomass of storage pool from previous time step. The first term of Equation (8) includes a coefficient 1.01 which allows for a luxurious uptake. The second term allows the plant to recover from nutrient deficit. Persistent nutrient deficit leads to an accumulation of starch and a reduction of photosynthesis.

Photosynthate and nutrients are used to grow plant parts. The degree-day of air temperature is used to initiate the leaf growth. Once the degree-day is satisfied, the canopy will grow according to the following equation:

$$GCANOPY = KCANOPY\ (PCANOPY - CANOPY) \tag{9}$$

where GCANOPY = growth rate of the canopy, KCANOPY = a rate constant, PCANOPY = canopy growth potential determined by the allometric relationship, and CANOPY = canopy mass at the time of evaluation. Equation (9) is a logistic function which grows canopy according to a S-shaped curve.

Biomass of canopy will die while the tree itself continues to grow. Each age class of the canopy is promoted to its next higher age class at the beginning of the year. Each year class has its own mortality to create litterfall,

$$LITTER = (CM)\ (MOZON)\ (MH2O)\ (CANOPY) \tag{10}$$

where LITTER = litterfall from an age class of canopy in grams, CM = mortality rate of the age class in percent per day, MOZON = mortality increase due to ozone concentration, MH2O = mortality increase due to water stress, and CANOPY = canopy biomass of the age class in grams. Litterfall is calculated for each age class and summed for the total. The total litterfall is then added to the litter content of the soil at the top layer.

The model includes the physiological stresses induced by ozone, aluminum, and water deficit. The model considers both sub-lethal and lethal effects. Sub-lethal effects of ozone cause stomatal closure. The model uses a dose response relationship between stomatal closure and ozone dose concentration (Figure 2). Another dose response function is used to determine a factor which amplifies the mortality rate of foliage to account for lethal effect.

The model uses modules from the ILWAS model (Chen et al. 1983, Gherini et al. 1985) to simulate soil hydrology and soil chemistry. A canopy module (Chen et al. 1983) is used to simulate the hydrologic processes of interception and evaporation and the chemical processes of dry deposition, wet deposition, foliar exudation, and throughfall. A snow pack module is used to simulate snowpack accumulation, snowmelt, and snowmelt leaching of ions.

The soil hydrologic module simulates the daily soil moisture. A soil temperature module simulates the daily soil temperature. The soil chemistry module calculates the concentrations of cations and anions, including the concentration of inorganic aluminum.

DEVELOPMENT AND TESTING

The computer program has been developed and is being tested. At this stage, the model performance is judged by its ability to function like a typical tree. Figure 3 shows 20 years' simulated tree ring for a hypothetical conifer grown in Panther lake watershed in the Adirondacks, New York. Such a simulation is not a trivial matter, because the model has to provide consistency among state variables for the tree, soil, and atmosphere. Model coefficients used in earlier tests often exhaust nutrients in the soil. More adjustment and even model modifications may be needed.

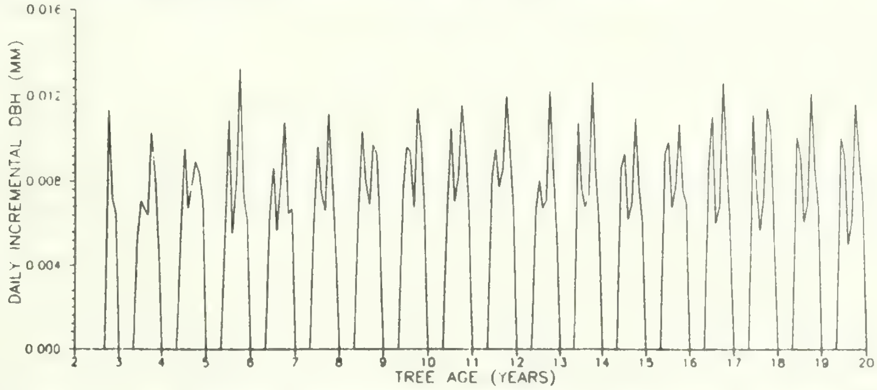

Figure 3. Simulated Tree Ring for a Hypothetical Conifer in Panther Lake Watershed of the Adirondacks, New York

The model will be tested for water and air pollution stresses, individually first and then jointly. The output of stomata opening index, photosynthesis rate, nutrient status, starch accumulation, litterfall and other parameters indicative of a stress sympton will be examined for their reasonableness.

DATA ACQUISITION

The model is design to simulate a specific tree at a specific site where data on tree, soil, and air can be monitored on a real time basis for model calibration. Since the model use parameters that can be adapted to any tree

at any site including laboratory condition, it is intended to apply the model to as many data sets as possible.

Some of the data can be derived from literature. Other data have to come from measurements conducted at the specific site. Literature contains information about the genetic blue print, growth physiology, and stress physiology of trees. Sometimes, the literature contains data which can be used to deduce the needed functional relationships. The information is often dispersed in numerous articles and is presented in different forms. It is necessary to review papers and to perform calculations that transform data into coefficients usable to the model.

Data on air, soil, and tree response must be measured at the tree site for model calibration. These data will be collected by the complementary research projects sponsored by the Electric Power Research Institute (EPRI) and the National Council of the Paper Industry for Air and Stream Improvement (NCASI). The bulk of data will be collected by EPRI's Response of Plant to Interacting Stresses (ROPIS). The laboratory and field studies of ROPIS are being conducted at the Cornell Univeristy, the University of California Riverside, and Tennessee Valley Authority.

To avoid the problem of modeling after data collection, the modelers and the researchers will participate in a number of workshops. In these workshops, the model theory and data requirements will be discussed. The model will be on hand to evaluate the sensitivity of model coefficients and to demonstrate the needs of certain data.

It is not possible to measure everything needed by the model. Occasionally, some estimates will have to be made by experts in the field. Some of these estimates will be made in the workshops. The reasonableness of the estimates will be evaluated by the model.

CALIBRATION AND VERIFICATION

The model will first be calibrated to plants grown under experimental conditions. The model will then be calibrated to trees in the field where environmental conditions change with time.

ACKNOWLEDGEMENT

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LABILE CARBON DYNAMICS IN A FLORIDA SLASH PINE PLANTATION

Wendell P. Cropper, Jr.[1]

ABSTRACT. A simulation model of a 29-yr-old slash pine plantation was extended to include a separate labile carbon pool and estimates of the growth and maintenance components of respiration for pine foliage, stems and branches, and roots. New tissue growth was assumed to equal litterfall, and phenological data were used to control the timing of new tissue production. Growth respiration was calculated on the basis of the biochemical requirements for tissue production, and maintenance respiration was simulated as a Q10 temperature response function.

The mild north Florida climate permits physiological activity throughout the year. The simulated seasonal pattern of the labile carbon pool depends on the input of gross primary production (2,507 $gC/m^2/yr$) and the outputs of new tissue production and growth respiration (406 $gC/m^2/yr$) and maintenance respiration (2,029 $gC/m^2/yr$). The simulated labile carbon pool peaked in early spring and summer, and was lowest in late spring and winter. Labile carbon dynamics were sensitive to the climatic input data used from normal, wet and dry years.

INTRODUCTION

Slash pine (Pinus elliottii) plantations in Florida have largely replaced the unmanaged pine forests that were dominated by longleaf (P. palustris) and slash pine. Although the plantations are similar to the natural forests that were replaced, tree density is higher and fire is less frequent in the managed plantations. Slash pine plantations are useful for forest ecosystem studies due to the relatively uniform structure and limited number of species present. Ecosystem studies of slash pine plantations at the University of Florida have included above-ground organic matter and nutrient dynamics (Gholz and Fisher, 1982), litter production and decomposition (Gholz et al., 1985), phenology (Hendry and Gholz, 1986), below-ground dynamics (Cropper et al., 1984, Gholz et al., 1986, Ewel et al., 1987a, 1987b), and simulation modelling (Cropper and Ewel, 1983, Golkin and Ewel, 1984, Cropper and Ewel, 1987, Ewel and Gholz, 1987). These analyses have identified water and nutrient availability as critical factors controlling slash pine productivity. It was also clear that additional information is required on canopy structure and physiological responses in slash pine plantations.

Studies are currently underway at the University of Florida manipulating nutrient and water availability through fertilization and drainage of plots within a plantation. Simulation modelling of the forest ecosystem

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has been a central focus for developing hypotheses and providing an explicit system-level description of processes and interactions (Golkin and Ewel, 1984, Ewel and Gholz, 1987). Model development is continuing in conjunction with the field studies. In earlier versions of the model structural and labile (metabolically active) carbon pools were combined in each state variable. This paper describes an extension of the model that includes a separate labile carbon pool for slash pine trees. This extension was made because combining pools with greatly different turnover rates may lead to interpretation difficulties and insufficient model resolution, and because labile carbon allocation patterns and respiration responses may be key components of the responses of slash pine trees to fertilization and drainage.

MODEL DESCRIPTION

The slash pine ecosystem model simulates the interactions of carbon, water and phosphorous using 22 nonlinear differential equations (Golkin and Ewel, 1984, Ewel and Gholz, 1987). The state variables for slash pine live biomass include foliage, stem and branches, coarse roots, fine roots in the litter layer, and fine roots in the mineral soil. The model also simulates understory, litter, and soil components. I extended this model in two ways: the slash pine state variables are defined as structural carbon compartments with a separate labile carbon pool, and respiration is simulated with separate maintenance and growth equations. Input to the labile carbon pool consists of slash pine gross primary production, and outputs are growth (increases in the structural carbon state variables), growth respiration, and maintenance respiration.

Maintenance respiration was simulated as a function of environmental temperature and tissue biomass:

$$mresp=Q10^{((temp-btemp)/10)}*k*biomass \tag{1}$$

where mresp is the maintenance respiration, Q10 is the rate of change of respiration per 10 degrees C change in temperature, btemp is a base temperature producing a k*biomass respiration rate, temp is the air or soil temperature (for roots), biomass is the size of the tissue structural carbon pool (g/m^2), and k is a constant. Growth respiration was calculated as a function of the amount of new tissue growth. Values of the additional carbon required for growth respiration in slash pine roots, stems, and needles were obtained from Chung and Barnes (1977).

The annual rate of net biomass increment in a 29-yr-old slash pine plantation is not large. For the purposes of this simulation I assumed that the amount of new tissue production is equal to the amount of litter fall or mortality (steady state). The timing of new tissue production was based on relative growth rates (Figure 1) from above-ground phenology studies (Hendry and Gholz, 1986), and on annual fluctuations of fine root biomass (Gholz et al., 1986) for the below-ground components.

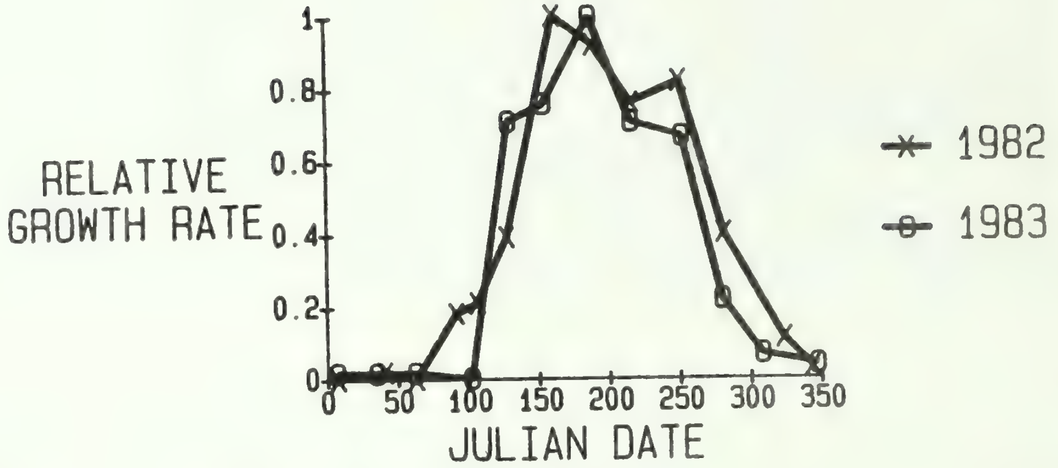

Figure 1. Relative needle growth rates for slash pine in 1982 and 1983 (after Hendry and Gholz, 1986.)

RESULTS AND DISCUSSION

Outputs of carbon from the labile pool consisting of maintenance respiration and growth carbon (growth respiration+new tissue production) follow a relatively smooth curve (Figure 2) associated with mean temperature. Gross primary production, the input to the labile carbon pool, responds strongly to variations in water availability and is more variable than respiration. Due to the slow turnover of structural carbon in the 29 yr old plantation, carbon output from the labile pool is dominated by maintenance respiration (Table 1). Although foliage is the smallest biomass component of the slash pine trees, it is highly active metabolically and contributes the largest removal from the labile carbon pool (Table 1). Foliage growth carbon allocation is about half of the standing crop of foliage biomass, whereas in the other

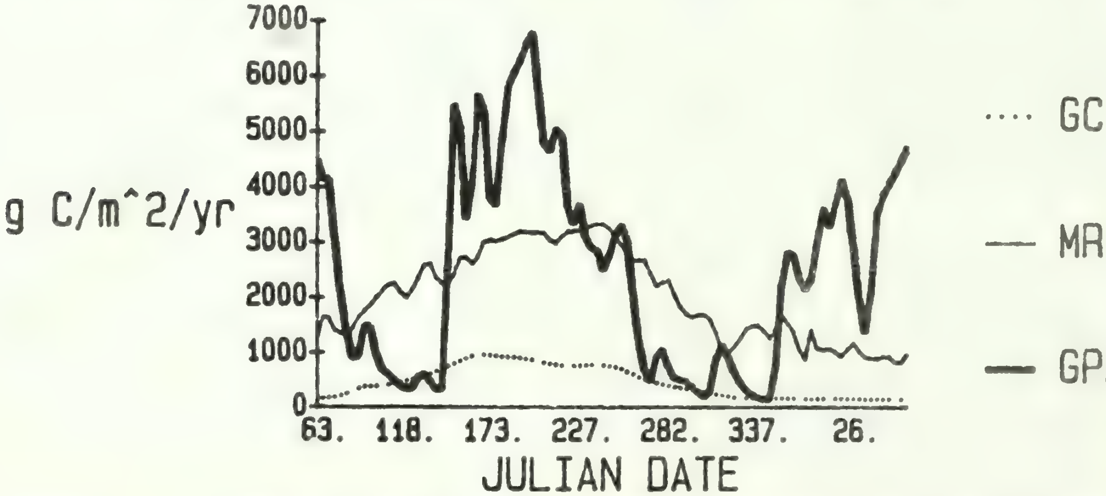

Figure 2. Annual variation in growth carbon (GC), maintenance respiration (MR), and gross primary production (GPP).

biomass components growth carbon is a small percentage of standing crops. The stem and branch component dominates slash pine biomass, but is relatively inactive metabolically due to the large proportion of non-living tissue and low growth rate. Labile carbon allocation to the roots accounts for a large fraction of the gross primary production. This result is consistent with observations of root production (Gholz et al., 1986) and soil CO_2 evolution (Ewel et al., 1987b). Annual variation within the labile carbon pool (Figure 3) shows two major peaks and two minima during the course of the year. The spring peak is associated with low rates of respiration and growth (Figure 2), whereas

TABLE 1. Distribution of biomass and labile carbon outputs for slash pine structural components

	Coarse Roots	Fine Roots	Stems+ Branches	Foliage
Biomass (g C/m^2)	1,000	438	7,458	426
Maint. Resp. (g $C/m^2/yr$)	214	499	656	659
Growth C.	13	125	58	210

the summer peak occurs during the period of highest gross primary production. The initial value of the labile carbon pool is a matter of conjecture at this time. Tissue carbohydrate analyses are currently underway that will provide an initial value and validation data for the timing of peaks and for the annual range of values. The magnitude of the annual range of the labile carbon pool during a year with typical rainfall is 495 g C/m^2 (Figure 3).

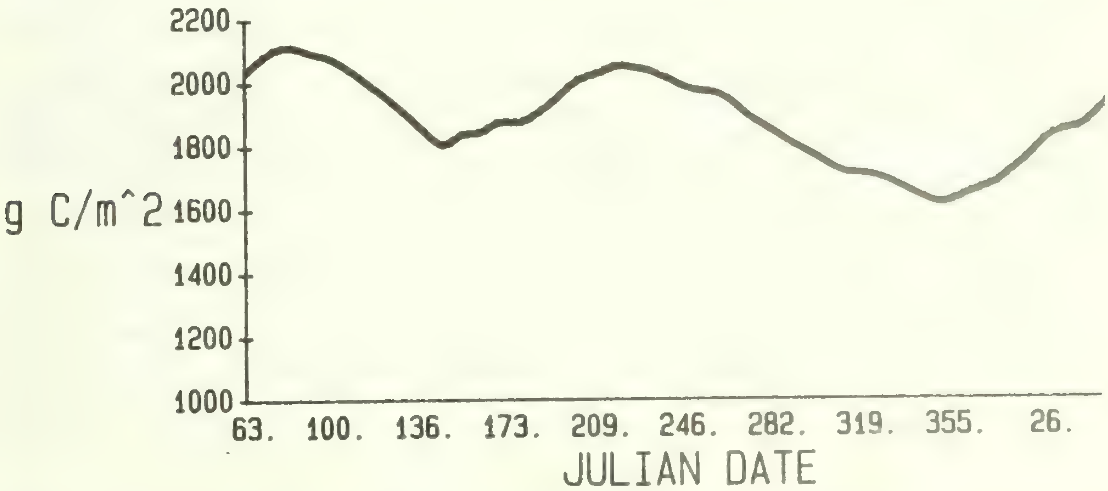

Figure 3. Simulated total labile carbon of slash pine trees for the normal rainfall year.

The weather input data, consisting of solar radiation, temperature, precipitation, and vapor pressure deficit, have a large influence over labile carbon dynamics. Growth phenology is not assumed to respond to weather, and the phenological data (Figure 1) do not show significant year-to-year variation in the timing of maximum growth rates. Even if growth responds to weather, the amount of carbon allocated for growth respiration and new tissue production in a 29-yr-old plantation is a small proportion of the carbon lost through maintenance respiration (Figure 2 and Table 1). Maintenance respiration and gross primary production do respond strongly to variations in the climate input variables. Maintenance respiration is simulated as an exponential function of temperature in equation (1), and gross primary production is a function of all of the climate variables. Simulated gross primary production is particularly sensitive to variations in water availability.

As a test of the sensitivity of labile carbon dynamics to climatic variation, the model was simulated using weather data from three different years (Table 2), representing dry, wet, and normal rainfall levels. The climatic input data used for this simulation were the same as used in Ewel and Gholz (1987) for climate sensitivity simulations. The labile carbon pool was highly sensitive to variations in climatic input (Figure 4). In the normal year respiration and growth losses balanced the input of gross primary production. In the dry year the labile carbon pool decreased, and in the wet year the labile carbon pool increased. Spring was particularly important in these simulations, with high gross primary production in the wet year, and low gross primary production in both the normal and dry years. The lower labile carbon standing crop in the dry year is primarily a reflection of lower gross primary production relative to the normal climate year (Table 3), whereas the higher labile carbon standing crop in the wet year is due in part to lower temperatures and maintenance respiration rates.

TABLE 2. Mean annual climatic parameters for 3 years.

	Solar input (MJ/m^2)	Temperature (deg. C)	Precipitation (mm/yr)
Normal year	7,092	21.3	1,318
Dry year	6,947	20.8	837
Wet year	5,844	18.7	1,406

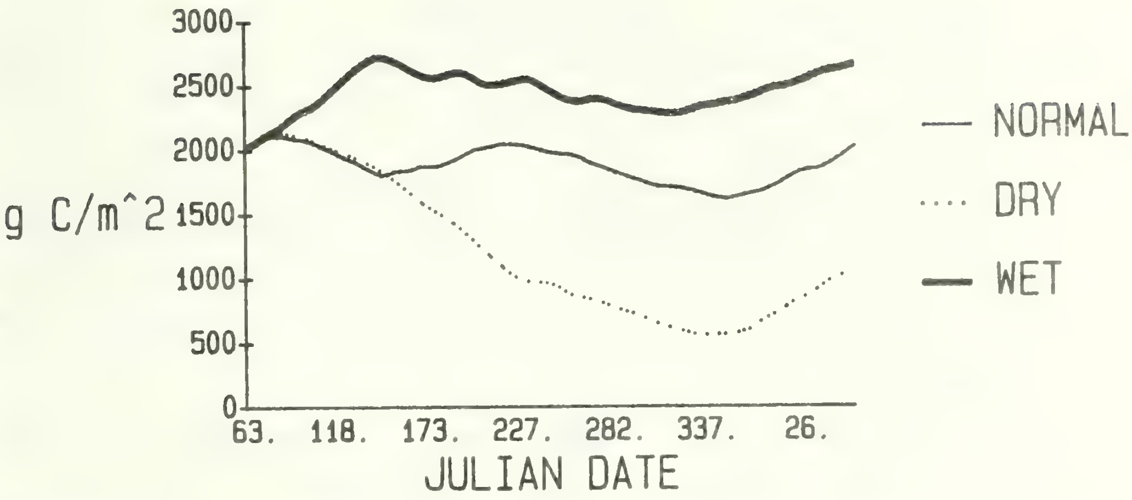

Figure 4. Simulated slash pine labile carbon dynamics for normal precipitation, dry, and wet years.

TABLE 3. Annual mean carbon dynamics for three climatic input sets.

	Gross Primary Production (g $C/m^2/yr$)	Maintenance Respiration (g $C/m^2/yr$)	Labile C Pool (g C/m^2)
Normal year	2,507	2,029	1,882
Dry year	1,692	2,182	1,208
Wet year	2,844	1,736	2,442

MODEL DEVELOPMENT

Fertilization and drainage studies are currently underway in an 18-yr-old slash pine plantation. The hypotheses being tested in this program are partly the result of previous simulation modelling (Ewel and Gholz, 1987). The data collected in these experiments will provide additional validation for the slash pine simulation model and a basis for increasing model resolution. New tissue growth and the associated growth respiration will be a more significant component of an 18 yr old plantation simulation. A separate labile carbon pool will be simulated for each slash pine state variable. This approach will require explicit simulation of carbon translocation within the trees. Labile carbon allocation pattern and respiration responses may be significant factors for understanding the responses of slash pine plantations to manipulations of water and nutrient availability.

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EFFECT OF TREE ARRANGEMENT ON INTERCEPTED RADIANT ENERGY AND PHOTOSYNTHESIS

Jennifer C. Grace[1]

ABSTRACT. A climate-driven model which estimates the interception of solar radiant energy and canopy photosynthesis for stands of *Pinus radiata* D. Don growing on fertile sites is presented. The model was used to investigate the effect of row orientation and tree spacing on intercepted photosynthetically active radiant energy (PAR) and canopy photosynthesis in agroforestry systems with 100 stems ha^{-1}. Row orientation was found to have little effect on annual canopy photosynthesis but produced a variation of about 10% in yearly intercepted PAR. Tree spacing had a greater effect. Yearly intercepted PAR and canopy photosynthesis were reduced by up to 23% and 11% respectively by spacing the trees closer together within the rows. On a seasonal basis, stands with rows orientated north-south intercepted, more PAR and had higher values of canopy photosynthesis during summer than stands with rows orientated east-west. The reverse was true in winter. These results also suggest that row orientation and tree spacing may affect carbon allocation patterns.

INTRODUCTION

Traditionally, models of forest growth have been derived from large mensurational data sets covering a range of management options and site conditions. Such models can be assumed to give reliable predictions of growth for stands growing on similar sites and subjected to similar management conditions provided that the site and/or management is well represented in the data set. Outside these ranges the models may not be reliable. For example, Manley (1986) showed that the basal area increment of heavily thinned stands of *Pinus radiata* D. Don with less than 225 stems ha^{-1} was overestimated using a model which had been derived using data from moderately thinned stands. At around 150 stems ha^{-1}, basal area could be overestimated by up to 60%.

An alternative approach which will estimate the effect of different management options on tree growth without recourse to large data bases is to develop models which simulate the biological processes controlling tree growth. Such a model is being developed to simulate the growth of *P. radiata* on sites where water and nutrients are non-limiting. This model should be applicable to the extensive commercial plantings of *P. radiata* in the central North Island of New Zealand where there are no serious water and nutrient limitations.

Currently the model simulates interception of solar radiant energy by a stand of trees,and canopy photosynthesis. Sub-models simulating respiration and allocation of carbon to different parts of the tree are being developed.

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As trees are often widely spaced in New Zealand (e.g. in newly-planted stands; in stands heavily thinned to produce quality sawlogs; and in agroforestry systems), the sub-model simulating the interception of solar radiant energy has been developed from the model of Norman and Welles (1983) in which the crown of each tree is represented by an ellipsoid. This model is considered adequate for calculating the interception of solar radiant energy when trees are widely spaced (Jarvis and Leverenz, 1983). Other features of the current model (Grace et al., 1987a) are that the position of each tree is specified, and that within the crown four shells can be specified. Within each shell the foliage is assumed to be randomly distributed, however the foliage, area density (foliage surface area per unit volume) can vary between shells, allowing for non-random distribution of foliage in the crown. A specified length of the crown, from the base upwards, may be removed. This allows simulation of green pruning regimes, and attack of pathogens at the base of the crown.

For each hour of daylight, the model calculates the hourly average intercepted solar radiant energy per square metre in the photo- synthetically active (PAR, 400-700 nm) and near infra-red (NIR, 700- 3000 nm) wavebands, taking into account the position of the sun, the proportions of diffuse and direct incoming radiant energy, and scattering. In order to calculate yearly intercepted radiant energy, the year has been split into three periods to take account of the variation in the sun's position, namely:

1. November, December, January, February,
2. March, April, September, October,
3. May, June, July, August.

For each period, the model is run for selected days covering the range of measured weather conditions. An equation predicting daily intercepted radiant energy from incoming radiant energy is then derived and used to predict daily intercepted radiant energy for each day (Grace et al., 1987a). Over a six-month period (January-June), the percentage difference in intercepted PAR from using the model on selected days (2 or 3 days/month) compared with running the model for each day was less than 3%, while on a monthly basis the percentage difference was less than 7% (Grace et al., 1987a).

Grace et al., (1987a) showed this model gave realistic estimates of the penetration of solar radiant energy through the canopy of a *P. radiata* stand; and that annual above-ground dry matter production was linearly related to modelled annual intercepted PAR for stands of *P. radiata* growing on a fertile site.

Net photosynthesis for a tree, on an hourly basis, is simulated by splitting the crown into a maximum of 52 segments and estimating the rate of net photosynthesis at a fixed point within each segment. This rate is assumed to apply to all foliage within that segment. Canopy photo- synthesis is obtained by summing over all segments for all trees within the stand. Yearly photosynthesis is obtained by running the model for selected days and using the same mathematical procedure as that used to calculate yearly intercepted radiant energy.

The rate of net photosynthesis is assumed to increase asymptotically with increasing incident PAR. The rate is reduced by increasing vapour pressure deficit (VPD) and increasing specific leaf area (SLA) (Grace et al., 1987b). Specific leaf area accounts for differences in rates of net photosyntehsis due to foliage age or position within the crown.

I report a simulation study in which the above model was used to investigate the effects of tree spacing and row orientation in agroforestry on intercepted PAR and canopy photosynthesis.

METHODS

The effect of tree spacing and row orientation on intercepted PAR and canopy photosynthesis was simulated for stands with 100 stems ha^{-1} assuming all trees were the same size and that the crown shape and leaf area index corresponded to the values measured in a 10-year-old stand with 100 stems ha^{-1} (Table 1) growing at Tikitere close to Rotorua (38° 9' S, 176° 16' E). This stand is being monitored for an agroforestry experiment (McQueen et al., 1976). Foliage was assumed to be evenly distributed within the crown. Spacings simulated are given in Table 2. East-west and north-south row orientations were simulated.

TABLE 1 - Average crown shape and leaf area index for a 10-year-old stand of *Pinus radiata* with 100 stems ha^{-1} growing on a fertile site. (Leaf area index given on a "one-sided basis.)

Tree height (m)	14.2
Crown length (m)	8.0
Crown width (m)	4.0
Leaf area index	1.14

TABLE 2 - Tree spacings, simulated annual canopy photosynthesis and intercepted PAR for stands with tree size given in Table 1

Stand	Spacing (m)		Canopy photosynthesis (t C ha-1 y-1)		Intercepted PAR (GJ m-2 y-1)	
	Between rows	Within rows	East West	North South	East West	North South
1	10.0	10.0	7.1	7.1	0.66	0.66
2	13.2	7.6	7.0	7.1	0.60	0.66
3	26.4	3.8	6.3	6.5	0.51	0.59
4	2.5/23.9	7.5	6.3	6.4	0.53	0.59

Note: Stand 4 planted in twin rows, see Fig. 1 for tree arrangement.

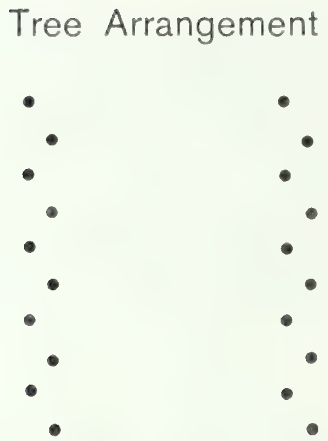

Figure 1. Tree arrangement for Stand 4 (Table 2)

Solar radiant energy data used to drive the model (Fig. 2) was collected during 1979 at Puruki (38° 30' S, 176° 15' E), an experimental forest about 40 km south-west of Rotorua.

The importance of year-to-year variations in incoming PAR was also investigated for Stand 1 (Table 2), using the equations relating daily intercepted PAR to daily incoming PAR with weather data measured at Puruki between 1980 and 1985.

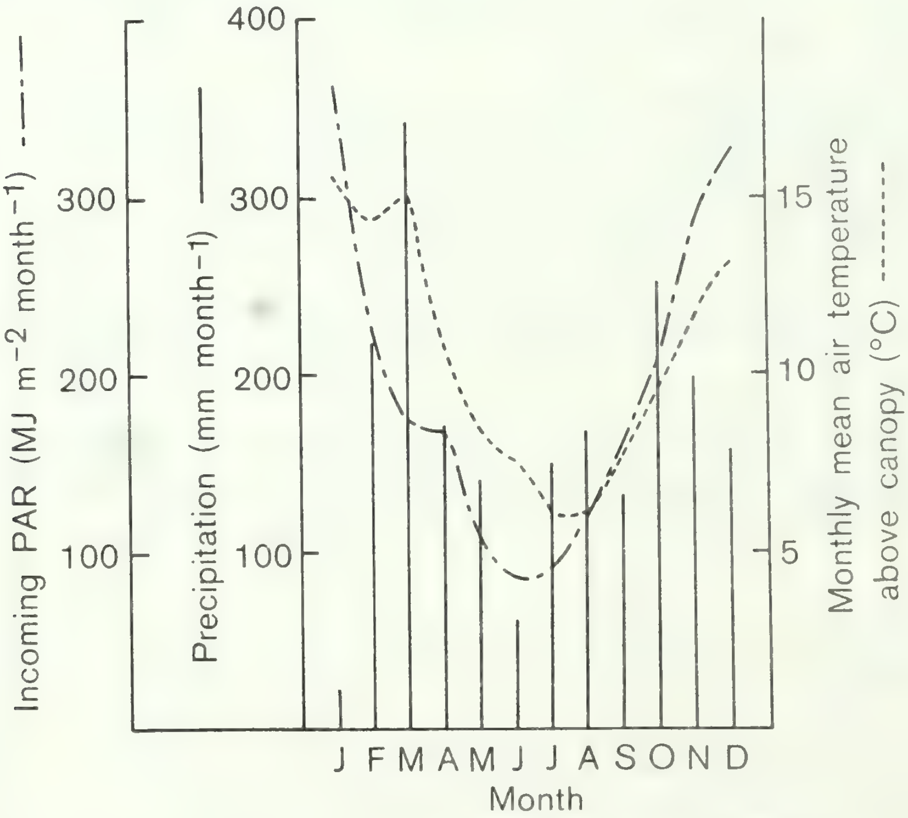

Figure 2. Climatic data for Puruki (38° 30' S, 176° 15' E) during 1979

RESULTS

ANNUAL PHOTOSYNTHESIS

For Rotorua, which is a temperate region where photosynthesis can occur throughout the year, the model showed a maximum of 3% difference in annual canopy photosynthesis for stands where rows were orientated east-west versus north-south (Table 2), with greater photosynthesis in the north-south orientation. On a seasonal basis, row orientation was more important. Simulated canopy photosynthesis for stands with rows orientated north-south was higher during summer and lower during winter than canopy photosynthesis for stands where rows were orientated east-west. The difference increased as within row spacing was decreased and between row spacing increased (Fig. 3).

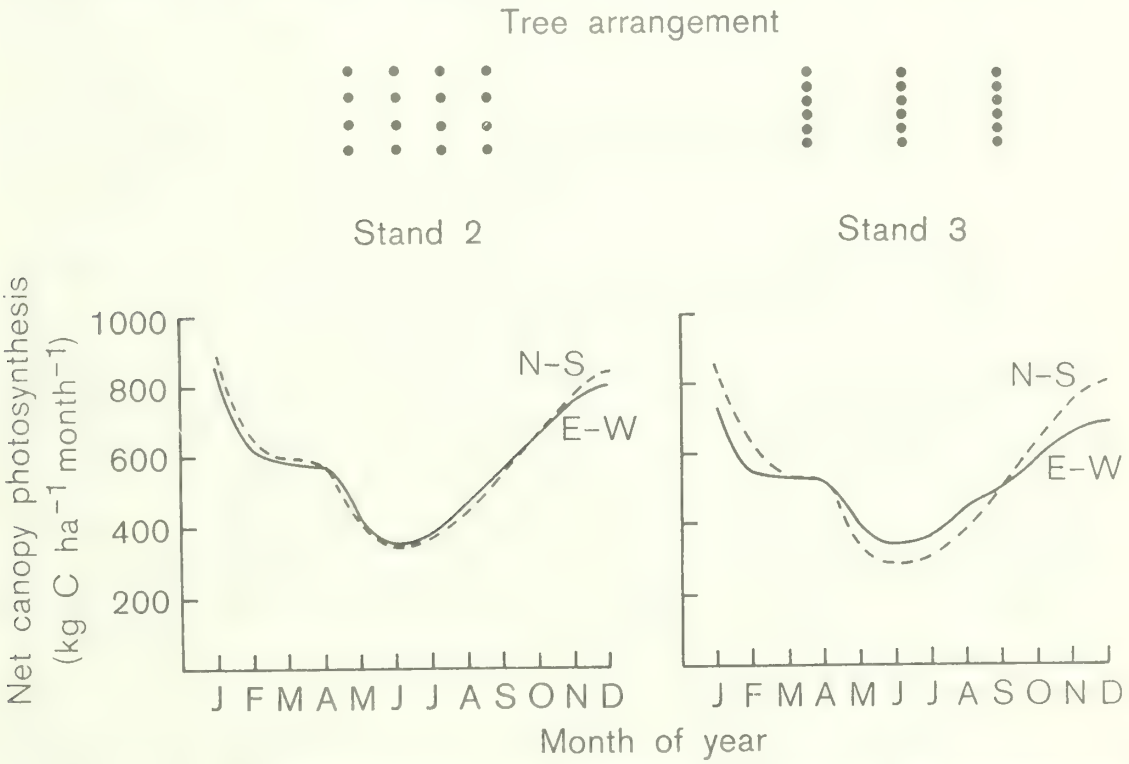

Figure 3. Estimated variation in monthly net canopy photosynthesis with tree arrangement and row orientation.

Tree arrangement had a greater effect than row orientation on simulated annual canopy photosynthesis and, over the range of spacings investigated, caused an 11% variation (Table 2). The closer together the trees were within rows the lower the estimate.

INTERCEPTED PAR

Stands where rows were orientated north-south intercepted about 10% more PAR per year than stands where rows were orientated east-west (Table 2). More PAR was intercepted during summer and less during winter by stands where rows were orientated north-south compared with stands where rows were orientated east-west (Fig. 4).

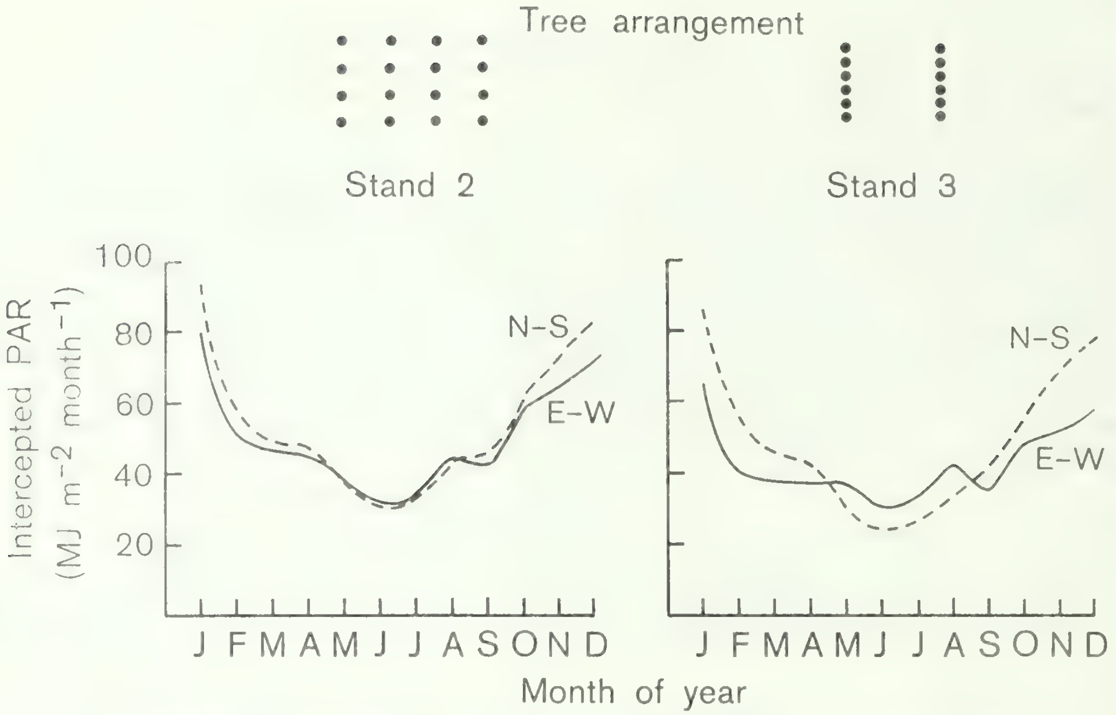

Figure 4. Estimated variation in monthly intercepted PAR with tree arrangement and row orientation.

As with canopy photosynthesis, yearly intercepted PAR was affected more by tree arrangement than by row orientation. The closer the trees within rows, the less PAR intercepted (Table 2).

For 1979, incoming PAR was 2.32 GJ m^{-2} y^{-1}. For the years July 1979-June 1980 to July 1984-June 1985, mean incoming PAR was 2.35 GJ m^{-2} y^{-1}, with a year to year variation of -2.3% to +2.4%. For Stand 1 (Table 2), variation in intercepted PAR was similar, being -2.4% to +2.7% about a mean of 0.67 GJ m^{-2} y^{-1} (Table 3).

TABLE 3 - Variation in simulated intercepted PAR for Stand 1 (Table 2) using solar radiant energy data collected at Puruki.

Period	Incoming PAR (GJ m^{-2} y^{-1})	Estimated Intercepted PAR (GJ m^{-2} y^{-1})
July 79 - June 80	2.29	0.65
July 80 - June 81	2.34	0.66
July 81 - June 82	2.40	0.68
July 82 - June 83	2.38	0.68
July 83 - June 84	2.34	0.66
July 84 - June 85	2.33	0.66

In 1979, the incoming PAR and intercepted PAR for the three seasonal periods used to run the model was within 7% of the means calculated using data and model results from 1979 to 1985. Hence the above results should be applicable for all years provided that the weather conditions are not abnormal.

DISCUSSION

For the tree size considered in this study, the results (Table 2) indicate that, the closer trees are within rows, the lower the annual intercepted PAR. Hence more solar radiant energy is available for understorey growth. This result is supported by studies at Tikitere. Stands with 100 stems ha^{-1} planted in twin rows and more regularly spaced rows initially showed little difference in pasture production, however from age 10 years onwards pasture production was greater in the stands with twin rows (N. Percival pers. comm.). The model also indicates that annual canopy photosynthesis is reduced by planting trees more closely within rows. For 10-year-old trees at Tikitere, basal area growth tended to be higher in the more regularly spaced stands (A. Koehler and R.L. Knowles pers. comm.) although the differences may be partly due to microsite differences.

The results (Table 2) indicate that both annual canopy photosynthesis and intercepted PAR are greater when rows are orientated north-south rather than east-west. Differences in canopy photosynthesis are negligible, however yearly intercepted PAR can vary by about 10% due to row orientation. Studies on *P. radiata* shelterbelts show no significant differences in height or basal area between shelterbelts with different orientation (A. Koehler, pers. comm.) suggesting that row orientation may not be important for tree growth.

In this simulation north-south rows intercepted more radiant energy during summer than east-west rows, a result also found in other studies (e.g. Jackson and Palmer, 1972; Charles-Edwards and Thorpe, 1976). Jackson and Palmer (1972) showed that, for continuous rows at latitude 34°, as the ratio of crop height to distance between crown projections of adjacent rows increased, the percentage difference in intercepted radiant energy due to row orientation decreased. The percentage intercepted radiant energy also varied with latitude, and in some instances east-west rows intercepted more radiant energy than north-south rows during summer. Hence the results shown in this simulation study will not necessarily be applicable to all latitudes where *P. radiata* is grown. Summer drought would also affect the results.

Data on incoming radiation for the years 1979 to 1985 (Table 3) indicated that the 1979 weather conditions used in this study were typical of the area. Hence these results should be applicable to all years provided that the climate is not abnormal.

The model, described in this paper, can be used to investigate many other management problems e.g., the effects of pruning, thinning and defoliation. However the full potential of process-based models will not be realised until there is a sound theory for allocation of carbon

between stems, branches, foliage and roots. At present the model is most suited to research studies. It is proposed to use the model to investigate the factors controlling allocation patterns.

When results from Table 2 are used to calculate the ratio of annual canopy photosynthesis to intercepted PAR, the ratio changes with row orientation and tree spacing. If above-ground dry matter production is linearly related to intercepted PAR as shown by several authors (e.g., Linder, 1985, Grace et al., 1987a), then row orientation and tree spacing should affect allocation and respiration patterns.

The model can also be used to highlight variables which are important in controlling tree growth. This study suggests that tree arrangement is more important for tree growth than row orientation in low-stocked stands that are found in agroforestry systems.

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A NEW BIOMATHEMATICAL MODEL FOR GROWTH AND YIELD OF LOBLOLLY PINE PLANTATIONS

Wade C. Harrison and Richard F. Daniels[1]

ABSTRACT. A new growth and yield model for loblolly pine plantations is proposed. The core equations of this model have a biological rationale: their structure is based on concepts of foliar carrying capacity and size-density relationships. This structure makes the model equally well-suited as a planning and inventory projection tool for forest managers or as a biological simulation tool for scientists in various disciplines. The model was fitted to data from spacing studies in the South Carolina Piedmont and Coastal Plain, and validated with survey data from permanent plots. Total basal area, number of trees, and product yields are projected either from stand establishment or existing stand conditions. Yield can be sorted into desired product classes using a stand level ratio approach or a Weibull parameter recovery model. For projecting tree lists or stand tables, tree level growth and mortality are predicted so as to be compatible with the stand level core estimates. Proposed routines for thinning, fertilization, and genetic improvement interact directly with model parameters to simulate the effects of intensive management practices.

INTRODUCTION

Resource managers have come to rely on mathematical models of forest growth and yield to aid in planning and decision making. Growth and yield information is used for long term strategic planning, projecting forest inventory, scheduling harvests, evaluating stand performance, and evaluating cultural alternatives. Different levels of model resolution may be required for each of these uses.

Perhaps more important than model resolution is the question of model rationale. The diversity of model uses and, with the advent of personal computers, the diversity of model users have placed new demands on models, not just for accuracy, but for flexibility, expandability, friendliness, and extrapolative properties. New cultural technologies and genetic material are constantly being introduced so that our forest populations are changing faster than ever. Predictions are needed before these new populations reach maturity.

While a great number of models have been developed for loblolly pine plantations (Pinus taeda L.), no single model can currently meet all of these needs efficiently. To do so will require a biomathematical approach to model building. That is, innovative mathematical formulations must be motivated by a strong biological rationale including an understanding of biological processes, responses, and their relevance to model structure.

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The objective of this work was to develop a new model of loblolly pine growth and yield which (1) is based on biological principles, (2) provides consistent growth and yield estimates when applied at the stand, size class, and individual tree levels; (3) is able to project existing stands and predict from bare ground conditions; (4) has the ability to simulate cultural and genetic alternatives; and (5) is applicable throughout the natural and extended range of loblolly pine.

DATA

Data from several long term designed spacing studies played a key role, both in the conceptual development of the model and in fitting the model parameters. All of these studies are 20 to 30 years old. The first is Westvaco's Loblolly Pine Management Study, which includes six square spacing treatments ranging from 1.2 to 4.2 meters. Multiple replications were installed at three locations on cutover land in the South Carolina Coastal Plain and Piedmont, representing site index classes of approximately 15, 20, and 23 meters (base age 25).

The second study is the spacing study on the USDA Forest Service Calhoun Experimental Forest near Union, S.C. (Balmer et al. 1975). This study includes four square spacings ranging from 1.8 to 3.6 meters. It was installed on a single old-field site, but exhibits considerable variation in site quality among four blocked replications with site index (base age 25) ranging from 17 to 22 meters.

Equally important to some of the conceptual developments were two loblolly pine spacing trials planted at Westvaco's subsidiary Rigesa Ltda. near Tres Barras, Santa Catarina in southern Brazil. Installed in 1961 and 1962, the treatments included square spacings ranging from 1.5 to 3.5 meters. The site index (base age 25) of these plots averages 35 meters.

Validation data for this study included first and second measurements of the check plots from the Virginia Tech Loblolly Pine Growth and Yield Research Cooperative study (Burkhart et al. 1985) and a set of permanent plots from Westvaco's Southern Woodlands in South Carolina. Data summaries of stand density effects from Borders and Bailey (1985) were also instrumental in the conceptual development and verification of the model.

MODEL DEVELOPMENT

There has been much discussion in the literature regarding the relative merits of stand level, size distribution, and individual tree based models for forest growth and yield prediction (see Munro 1974, Daniels et al. 1979, Burkhart 1979). Daniels and Burkhart (in press) further discuss methods for combining these approaches into an integrated system, capable of several levels of resolution. Their approach started at the individual tree level, collapsing and aggregating model components to form a stand average growth model.

We have taken an approach to model architecture which is similar in spirit, but opposite in direction. Our model is integrated in resolution, but begins with the forest stand as the fundamental unit of productivity.

The model is driven by a "biomathematical" core -- stand level equations for basal area and survival, which behave according to ecological theory and physical constraints. Growth of individual trees, expressed as a tree list or stand table, is then estimated in a manner which is mathematically consistent with the stand level predictions. Structurally, the approach is similar to those of Clutter and Allison (1974) and Clutter and Jones (1980), although the specifics may vary considerably.

STAND LEVEL CORE

Basal Area

Widespread in forest ecology literature is the concept that, soon after crown closure, stand foliage mass or leaf area per unit area approaches an equilibrium level which is dependent upon site resources. This constant foliage level can be considered the asymptote of a sigmoid development curve. The asymptote is independent of stand density, whereas approach toward the asymptote may be density dependent. Several investigators have shown the proportionality between leaf area and the cross sectional area of conducting xylem or the "pipe" supplying water to the foliage. Hence, sapwood basal area should follow a similar asymptotic sigmoid development curve. Long and Smith (1984) provide an excellent summary of literature on foliage development and sapwood area - leaf area relationships. If the relationship between sapwood and total basal area were known, this transformation applied to the sapwood development curve would provide us with a biologically derived model of total basal area. For relatively young loblolly pine on pulpwood rotations it seems safe to assume that total tree basal area follows at least a similar shape. (In older stands the accumulation of heartwood would imply an increasing level of basal area). Thus the first component of our stand level core is an asymptotic sigmoid model of basal area per unit area.

Note that the asymptotic basal area model implies a relationship between average size and density, known in much of the literature as the self-thinning rule (Yoda et al. 1963, White and Harper 1970). This rule has been widely applied as a forest management tool (Reineke 1933; Drew and Flewelling 1977, 1979). For a self-thinning stand, basal area (BA) approaches a constant, so mean tree basal area ($\overline{B}$) approaches an inverse relation to number of trees (N):

$$BA = a$$
$$\overline{B} = a\,N^{-1} \quad \text{or} \quad \ln \overline{B} = \ln a - \ln N$$

As long as basal area is approaching its asymptote and the number of trees per acre is decreasing, the self-thinning trajectory (on a logarithmic scale) approaches a straight line (Figure 1a,b). No matter how stand survival is expressed, the asymptotic basal area model implies a self-thinning slope of -1 for mean basal area or -.5 for quadratic mean diameter. Note that size attributes which continue to increase during self-thinning, such as total volume or weight, result in self-thinning slopes steeper than -1.

Several researchers have developed explicit models for the self-thinning line or a stand's trajectory toward it (Smith and Hann 1984, 1986; Lloyd

and Harms 1986). Weller (1987a,b) and Zeide (1987) point out statistical and conceptual uncertainties associated with the self-thinning rule. We chose not to model self-thinning trajectories directly. However, the relationship is implicit in our model because we based it on the underlying process of self-thinning: the development of a relatively constant mass of foliage and its redistribution among a decreasing number of stems (Long and Smith 1984).

The level or intercept of the self-thinning line is determined by the level of the basal area asymptote (Figure 1a,b). We will call this level the carrying capacity for basal area. Strub and Bredenkamp (1985) reported that carrying capacity increases with increasing site quality for loblolly pine in South Africa. Data from our long term spacing studies installed over the range of sites in South Carolina and in southern Brazil corroborate these findings. Estimated self-thinning lines were significantly different in intercept by site, but not different in slope. Thus our basal area model takes an asymptotic form, with the asymptote determined by site quality and rate determined by stand density.

An exception to the concept of asymptotic basal area can occur, particularly in dense stands. Basal area per unit area may approach its carrying capacity and then decline or "crash" substantially with a major

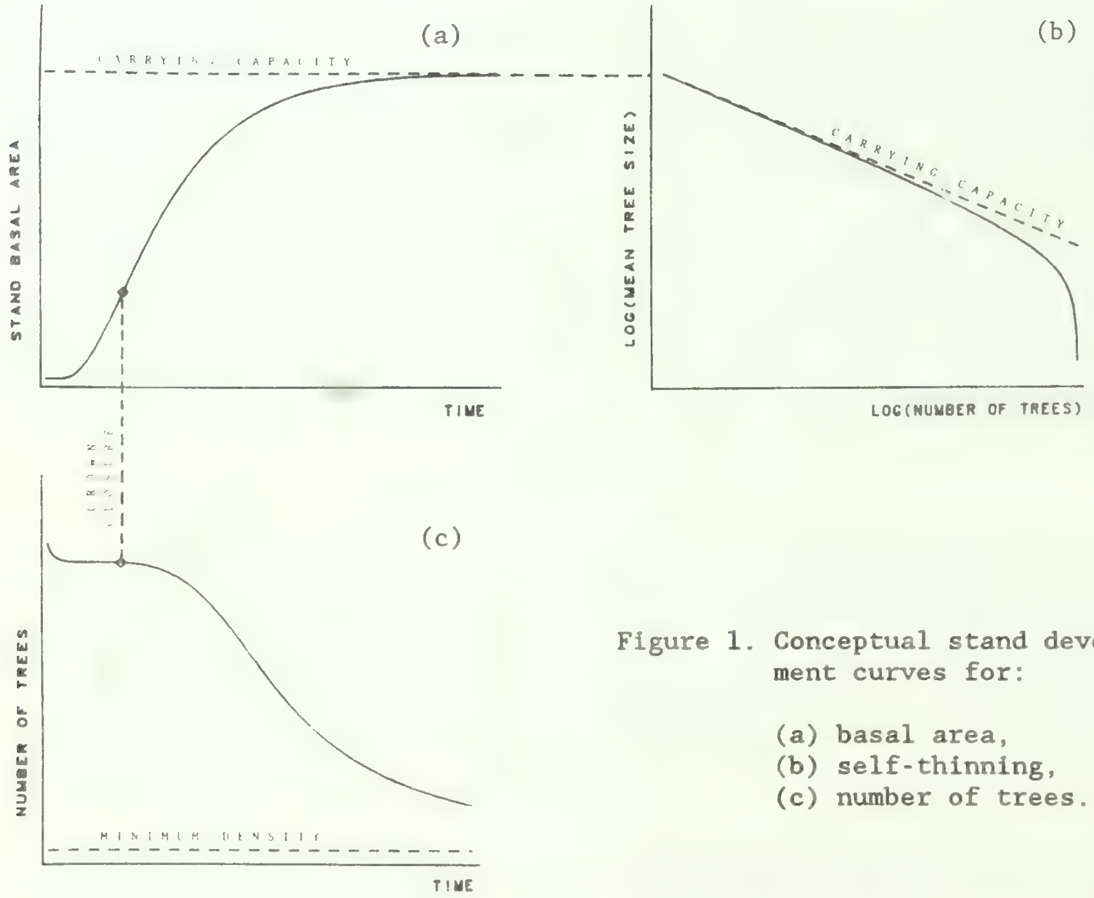

Figure 1. Conceptual stand development curves for:

(a) basal area,
(b) self-thinning,
(c) number of trees.

wave of mortality. We have consistently observed this basal area crash in our spacing studies for spacings closer than 2 x 2 meters. The model of Hafley et al. (1982) explicitly addresses this phenomenon with predicted declines in stand yield and basal area after attaining density specific maxima.

We propose to model the crash phenomenon explicitly with a function to reduce basal area from the asymptotic model as average tree sizes approach a biophysical imbalance. This model implies a slow recovery towards carrying capacity as survivors grow. The loss in number of trees is modeled directly in the survival function described below.

Survival

Survival is the second component of the stand level core equations. The phase of mortality in which we are most interested is density-dependent or self-thinning mortality. We considered this phase to begin around the time of crown closure. Mathematically, the inflection point of the basal area model was chosen to estimate this point (Figure 1a,c). The surviving number of trees per unit area is a monotonic decreasing function of time. We further consider that survival approaches a lower asymptote, interpreted as the fewest number of trees of maximum size which fully utilize the site (Figure 1c).

Height

A third component of the stand level core is dominant height. Height development by site is predicted with a classic familiy of site index curves. Further, dominant height rather than age was adopted as the independent or predictor (time) variable in the basal area and survival models discussed above. The purpose of this transformation was to account for both site and age in one predictor. Many relationships with age which had to be qualified by site were much clearer when examined over height. While using dominant height as the predictor variable places a great deal of emphasis in application on the site index curve, the approach offers flexibility by introducing different development patterns through the shape and level of the site index curve.

Model Forms

The model form chosen for stand basal area (BA) was a generalized form of the familiar Richards function (Pienaar and Turnbull 1973), where the time variable is dominant height (H). The model is conditioned to give zero basal area when dominant height is equal to breast height (h):

$$BA = a\,(1 - e^{-b(H-h)})^{c} \qquad (1)$$

Parameters a, b, and c are fuctions of site index (SI) and the number of trees established per unit area (NE):

$$a = a1\ SI$$
$$b = b1\ NE^{b2}$$
$$c = c1\ SI^{c2}$$
$$a1,b1,b2,c1,c2 = \text{fitted parameters}$$

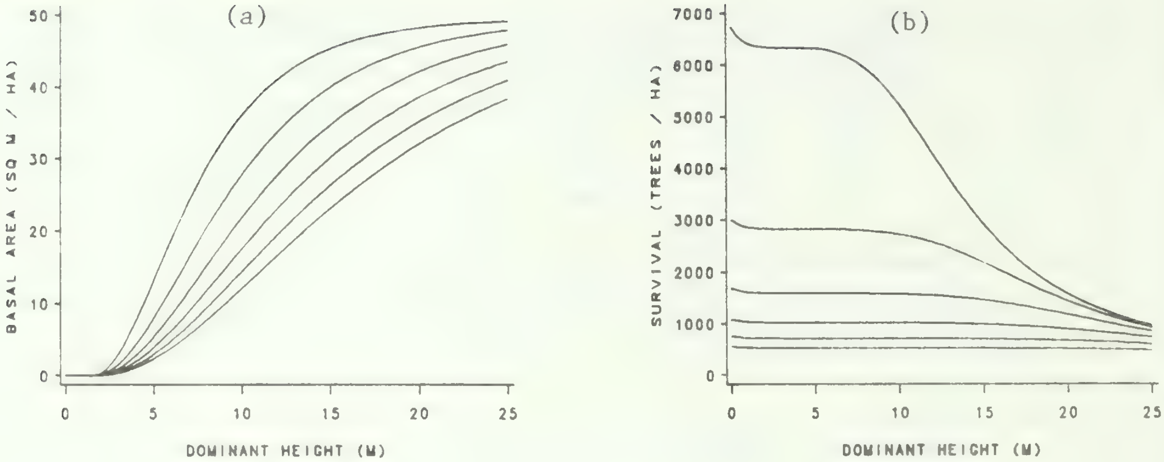

Figure 2. Model-implied development curves for (a) basal area and (b) number of trees surviving, for six different establishment densities. Site index is held constant.

This formulation of the basal area model is appropriate for non-declining estimates of basal area from bare ground starting conditions. Figure 2a illustrates predicted basal area development for several establishment densities. Note that this formulation of the model does not account for the tendency of high density stands to "crash."

Frequently, we have an initial value of basal area which we wish to project into the future, while establishment density (NE) is unknown. An advantage to our model formulation lies in our ability to solve for the stand-specific rate parameter (b) using initial basal area (BA_1) and initial dominant height (H_1). Thus, establishment density is unnecessary information when initial values of basal area and dominant height are available. The solution for b may then be substituted into equation 1 to obtain projected basal area (BA_2) for any projected dominant height ($H_2 > H_1$):

$$BA_2 = a \{1 - [1 - (BA_1/a)^{(1/c)}]^{(H_2-h)/(H_1-h)}\}^c \qquad (1a)$$

An additional advantage to this model formulation is that we can write out an expression for the inflection point of basal area development, or the height at which basal area growth (per unit of height growth) is maximized (H_c):

$$H_c = [h\ b - \ln(1/c)] \ / \ b$$

This time of inflection is a logical indicator of crown closure and the start of density-dependent mortality, or self-thinning. For survival prior to this time, a declining exponential function of dominant height serves to reduce establishment density to the density at crown closure (N_c). After crown closure, density-dependent mortality is expressed with a model first introduced by Clutter and Jones (1980). We formulated this model as a function of dominant height, and included a lower asymptote representing the minimum number of trees required to fully utilize

the site (N_{min}). The combined system for predicting the number of surviving trees per unit area (N) is:

$$N = NE \, [s + (1-s) \, e^{-.5 \, H}] \qquad \text{for } H < H_c$$

$$N = N_{min} + [(N_c - N_{min})^p + q \, (H^r - H_c{}^r)]^{1/p} \qquad \text{for } H > H_c \tag{2}$$

where $N_c = s \, NE$
p,q,r,s = fitted parameters

Based on maximum size records for loblolly pine, we estimate N_{min} to be about 60 trees per hectare. Because we lack data for stands at this lower limit of density, this value is at best a guess. However, the model's performance is not very sensitive to the value chosen.

As specified here, the survival model generates survival curves from bare ground conditions (Figure 2b). To apply the survival model to project initial density (N_1) in an existing stand, substitute N_1 and H_1 in equation 2 for N_c and H_c, respectively.

An additional model was developed to account for the basal area crash in high density stands, where asymptotic predictions of basal area growth do not reflect observed stand development. The ratio of observed basal area in stands exhibiting a crash to the predicted asymptotic basal area for that stand forms a "crash factor" (CF). The prediction model for the crash factor was based on relative spacing, the ratio of the average distance between trees to dominant height (Hart 1928, Beekhuis 1966). Relative spacing is appealing as an indicator of the crash because it is readily computed from the model estimates of height and survival, which are well-behaved in dense stands.

The first derivative of relative spacing with respect to height (dS/dH) proved to be a reasonable predictor of the crash factor. A near zero derivative indicates that the stand has reached a biophysical limit to density. A simple asymptotic model describes the relationship:

$$CF = 1 - e^{-k1} \, (k2 + dS/dH) \tag{3}$$

where $k1, k2$ = fitted parameters

The revised estimate of stand basal area is computed by multiplying the basal area estimate from the asymptotic model (Equation 1) by the crash factor (Equation 3). Figure 3 illustrates the effect of the crash on basal area development.

Apart from the crash, the biomathematical core models closely resemble models presented by Kenney (1983) and Pienaar and Shiver (1984). These models also express stand growth using a generalized Richards function for basal area coupled with a decreasing survival function.

STAND YIELD

The core models describe the dynamics of stand development. To estimate stand yields two approaches were taken. The first is the method of stand

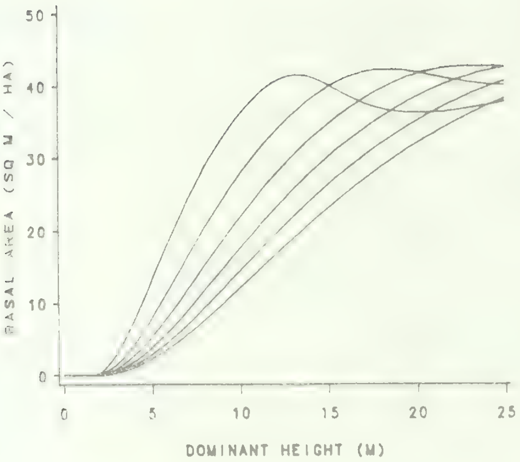

Figure 3. Model-implied basal area development curves for six different establishment densities, after applying the crash factor. Site index is held constant.

level ratio described by Amateis et al. (1986). The second approach was a Weibull distribution parameter recovery technique for generating a diameter distribution (Hyink and Moser 1983). The core basal area and survival models provide the estimate of the second diameter moment. Equations for other moments, order statistics, or quantiles of the diameter distribution are easily modeled with respect to quadratic mean diameter. The addition of a typical model for average height per diameter class allows prediction of tree weights and volumes which are summed to estimate stand level yield products of interest. Both approaches are well-documented in the literature and, for the sake of brevity, will not be discussed in further detail.

TREE GROWTH AND STAND TABLE PROJECTION

While both stand yield approaches are useful when a stand is projected from bare ground, neither can use information on the size structure of an initial stand when a projection is desired. Initial stand information, such as a tree list or a stand table is frequently available for inventory projections.

For such situations, we sought a method of distributing the stand level estimates of basal area growth and survival (Equations 1,2) among individual trees or size classes. This approach avoids the simplifying assumption that tree diameters follow a particular distribution such as the Weibull, without loss of simplicity. Individual tree measurements from the USDA Forest Service Calhoun spacing study were used to develop the models.

Model Forms

We chose to estimate survivor trees by distributing total stand mortality across the distribution of initial tree diameters. This was accomplished by modeling the cumulative proportion of total stand mortality (M) across tree dbh scaled between its minimum (Dmin) and maximum (Dmax):

$$M = (1 - e^{-b\ X}) / (1 - e^{-b}) \qquad (4)$$

where $b = b1\ N^{b2}\ H^{b3}$
$X = (Dbh-Dmin)/(Dmax-Dmin)$
$b1, b2, b3$ = fitted parameters

The proportion of mortality represented by each individual tree or size class is computed by subtracting successive values of the cumulative distribution.

We propose a model for basal area growth of survivor trees (ΔB) in terms of initial tree basal area (B), conditioned to ensure compatibility with stand-level basal area growth. Within a stand, tree growth is linearly related to initial tree size (Hilt 1983, Zeide 1985):

$$\Delta B = a + b\ B$$

This simple linear equation can be rewritten without the intercept (a), and the slope (b) may be generalized across stand conditions. Note that total basal area in survivor trees (BA_s) and total basal area in mortality trees (BA_m) can be obtained by applying equation 4 above to initial stand data. Projections of stand basal area (BA_2) and survival (N_2) are available from the core models (equations 1 and 2):

$$(\Delta B - \overline{\Delta B}) = b\ (B - \bar{B}) \qquad (5)$$

where $\overline{\Delta B} = (BA_2 - BA_1 + BA_m)/N_2$
$\bar{B} = BA_s/N_2$

$b = b1\ e^{b2\ SI}\ H^{b3}$
$b1, b2, b3$ = fitted parameters

INTENSIVE CULTURE

The system of stand and tree models just described lends itself well to the inclusion of routines for describing intensive cultural responses and genetic improvement. We have proposed mechanisms to simulate the effects of thinning, fertilization, competing vegetation, and genetic improvement by identifying the key model parameters affected by these factors. The methods of Pienaar (1979) are well suited for incorporating thinning into this model. Nutrition and genetics can affect the level and/or the approach to the self-thinning line, which translate into asymptote and rate parameters for basal area and survival. Such effects may also be introduced through the site index curve (Buford and Burkhart 1987, Nance et al. 1987). Weed competition may reduce the effective carrying capacity, either temporarily or over the rotation, and may also directly influence rate parameters. Our operational model includes mechanisms to modify model parameters to simulate these hypothesized effects for further testing and validation with experimental data in the coming years.

DISCUSSION

The model described in this report is a foundation for planning and inventory projection systems. The biomathematical rationale and observed

behavior inspires confidence among users. Equally important is the ability to obtain consistent estimates among all of the various applications for growth and yield data. For example, inventory projections are consistent with long term strategic yield expectations. The model can also be used in harvest scheduling and operational decision making. A user-friendly software system will place the model and other applications in the hands of decision makers at all levels of management.

Besides its immediate utility, the model provides a structure for future technological advances, a framework for further study. Physiologists, silviculturalists, and geneticists interested in the model will help refine the concepts and applications. For example, refinements in the relationships between foliar biomass, sapwood basal area, and total basal area will strengthen the model's theoretical basis. Mensurational refinements in site index and tree weight and volume methodology can be incorporated directly into the model. The integrated model structure, in particular the stand level core, lends itself well to the concept of simultaneous parameter estimation, another area of future refinement.

The model structure presented here is well-suited to industrial information needs for managing loblolly pine plantations. We believe it will be applicable for many other forest types and resource management organizations.

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FORCYTE-11: AN EXAMPLE OF THE HYBRID SIMULATION APPROACH TO PREDICTING THE CONSEQUENCES FOR PRODUCTION, YIELD, ECONOMICS, SOIL FERTILITY, NUTRIENT AND ORGANIC MATTER RESERVES, AND ENERGY EFFIENCY OF ALTERNATIVE CROP PRODUCTION SYSTEMS

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ABSTRACT. The eleventh version of the FORCYTE series of models is a flexible, ecosystem-level modelling framework capable of simulating most aspects of single or mixed-species even-aged forest or agroforestry crop production systems. FORCYTE-11 simulates both nutrient cycling and nutrient feedback on growth, and within-canopy light intensity profiles and the effects of shading on the production efficiency of foliage. The hybrid approach to yield prediction is explained and the model is briefly described. The application of FORCYTE-11 in tropical agroforestry is discussed as an example of the model's capabilities. Future development of FORCYTE will include an explicit treatment of moisture as a limiting factor, and improvements in the resolution of events that occur in the early years of stand establishment to make the model more useful as a vegetation management research tool.

INTRODUCTION

Predictions of future forest growth have traditionally been based on an "historical bioassay": the growth achieved over the past rotation. This is probably the best approach to yield prediction if the future growing conditions are the same as those of the past. The record of past growth integrates the effects of all the factors that have influenced trees on the site over the entire rotation, and such historical bioassay (HB) predictions are not limited by either our still incomplete understanding of the determinants of forest growth, or our limited ability to quantify those determinants.

Unfortunately, the relationship between stand age and biomass accumulation which is the basis for HB yield predictions is changed if one or more of the major determinants of tree growth are significantly altered in the

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future. Changes in edaphic, climatic and biotic determinants of growth can alter the temporal pattern of production and biomass accumulation on a site, thereby reducing the accuracy of HB-based yield predictions. New HB yield predictors can be prepared for the new growth conditions, but this usually requires measurement of biomass accumulation over another crop rotation. The long time requirement of HB preparation can result in many decades of inaccurate yield predictions, and there is a significant risk that management and environmental conditions may have changed yet again by the time the new HB has been prepared. This problem has been referred to as "future shock" in yield forecasting (Kimmins 1985).

The inability of HB yield predictors to predict forest growth accurately under changed future growth conditions was recognized by German mensurationists as early as the mid-nineteenth century (Assman 1970). They concluded that forest yield should be predicted on the basis of an understanding of the determinants of forest growth, and estimates of how these determinants will change in the future, rather than on the record of past tree growth. This conclusion became the basis for the subsequent century of process-oriented research on forest production and yield, and the process simulation models that have been developed therefrom. Conceptually sound, and extremely valuable in education and research, such process-simulation models have yet to be accepted by forest managers as a practical means of predicting yield. Process models of forest growth have tended to be either too simple to account for all the significant determinants of growth (and are therefore inflexible), or they have become extremely complex where attempts have been made to include all (or a large number of) significant determinants. Lack of adequate calibration data, lack of access to sufficiently powerful computational facilities, and/or lack of understanding of the internal workings of very complex process models has acted to limit acceptance of this type of model by forest resource managers.

This paper describes an alternative to the HB and process simulation approaches to forest yield predictions: the hybrid simulation approach. An example of a hybrid yield simulator, the FORCYTE series of ecosystem models, is briefly introduced. More details of this model can be obtained in Kimmins (1986a, b), or in the User's Manual (Kimmins and Scoullar 1987).

THE HYBRID SIMULATION APPROACH

In spite of their shortcomings, both HB and process simulation approaches to yield prediction have significant advantages. HB yield predictors are the most believable for futures that are the same as, or very similar to, the past, but cannot predict growth accurately for significantly altered futures. Process simulation predictors theoretically have the flexibility to predict yield under a wide variety of future conditions, but in actuality they generally share with HB predictors the problems of inflexibility because they usually do not account for all major growth determinants that may change in the future.

The hybrid simulation approach involves combining these two approaches, using the major strength of each approach to compensate for the major shortcoming of the other. The HB approach provides the best estimate of

the future net biomass accumulation by a particular crop on a particular site under the conditions that pertained over the past rotation. By combining this estimate with a simulation of those major growth-determining processes that will be altered under the set of future conditions for which you want a yield prediction, the hybrid simulation approach is able to evaluate whether or not the HB yield predictions will be achieved. Under improved growing conditions, growth may exceed HB predictions. Under less favourable circumstances, the HB predictions may be overly optimistic.

There is no single "best" design for a hybrid simulation model. The processes that are to be simulated will depend entirely on the intended application of the model. For example, if the major expected change in growth-determining conditions between the past and the future is the availability of nutrients (caused, for example, by a change from conventional to whole-tree harvesting), nutrient cycling processes should be simulated and used to assess whether or not the HB predictions can still be achieved. Yield prediction under such changed utilization standards does not require a simulation of temperature and moisture effects on growth since these are already represented in the HB, and they are not altered by changing utilization levels. In contrast, prediction of yield under altered future climatic regimes would require a simulation of direct temperature and moisture efects on plants as well as of the effect of these climatic changes on nutrient cycling and other processes.

Inclusion of a process in a hybrid simulator is therefore determined by whether or not the user believes that the factors determining that process will be changed in the particular future the user wishes to predict. In many applications of the model, it will not be necessary to include a simulation of a large number of determinants of growth. Other applications may require a much more complex set of simulations. It is not possible at the present time to include a simulation of all determinants of growth, and even if it were, it would probably result in a model of such size and complexity that the model would have little value for forest managers as a yield predictor.

FORCYTE* AS AN EXAMPLE OF A HYBRID SIMULATION MODEL

There are several examples of the hybrid simulation genre of yield prediction model. Most of these (e.g. FORTNITE (Aber and Melillo 1982); FORET (Shugart 1984); a nutrient version of FORET (Weinstein et al. 1982); LINKAGES (Pastor and Post 1985)) can be traced back in their development to the JABOWA model of forest succession (Botkin et al. 1972). The FORCYTE series of models has a broad similarity to the JABOWA-derived series of models, but was developed from the outset as a series of forest management simulators rather than as an ecological research tool. There has been some convergence between the two lineages of model, the JABOWA-derived series becoming increasingly useful as forest management models, and the FORCYTE series becoming increasingly useful for research on ecological processes such as succession. The convergence is not yet

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*FORCYTE: FORest nutrient Cycling and Yield Trend Evaluator

complete, and the two different lines of development still have their own unique features and advantages.

FORCYTE is an ecosystem-level, hybrid simulation, stand production and yield model. It can represent any desired combination of a variety of plant life-forms (trees, shrubs, herbs, mosses, and, for tropical agro-forestry applications, bamboo), and, according to which version of the model is used, a variety of soil, management, and other growth-determining processes or events. All FORCYTE versions explicitly simulate nutrient cycling in geochemical, biogeochemical and internal cycling pathways, and nutritional limitations on growth. This nutritional basis for yield prediction does not imply that nutrients are necessarily the most important determinant of growth, but that the nutritional status of a site is one of the growth-determining site parameters that is most susceptible to change as forest management practices change.

FORCYTE-10 can only simulate one limiting nutrient. FORCYTE-11 can simulate up to 5 nutrients. The eleventh version of FORCYTE adds a simulation of canopy light conditions in order to permit the simulation of species mixtures, and an improved simulation of management-induced changes in stand structure and stand density (Kimmins et al. 1986). This addition permits the model to be used to examine light competition, early secondary succession, and various strategies of "vegetation management" (weed control), as well as the improved simulation of the response of tree and understory growth to thinnings. The planned twelfth version will include explicit representations of temperature and moisture effects to facilitate the use of the model in the prediction of yield under changed future climatic conditions and the effects of vegetation management and stocking control in moisture-limited environments.

All versions of FORCYTE are stand-level models which are driven by inventory-type, stand-level, historical bioassay input data, together with data that define the growth-limiting processes that are to be simulated. FORCYTE-11 and subsequent versions also represent the growth of individual trees. This is achieved by allocating predicted annual stand production between the surviving plants using a distance-independent algorithm derived from input stand table data on stem biomass (derived from dbh) distributions. This approach appears to work well but requires further testing before its quantitative performance can be reported. It is anticipated that the approach will require further refinement to achieve the desired performance in predicting the response of diameter distribution to thinning.

A feature of all the versions of FORCYTE is the ability of the user to control both the action and the rates of all simulated processes via a series of input data files. This permits the model to be used in a variety of configurations. The user may choose to switch off many of the process simulations, thereby reducing FORCYTE to essentially an historical bioassay-type of yield predictor (not its intended use). Alternatively, the user may opt to include the simulation of any combination of a variety of soil and plant processes. Where a particular process is well understood, where reliable calibration data are available, and where it is believed that future changes in the process will significantly affect production and yield, the user may wish to include the process in the

yield prediction. Where this is not the case, the user may omit the simulation of that particular process or may use the model to examine the possible yield consequences of various assumptions about the process. Users are reminded that omission of a process from a yield model can result in a prediction error that is as large as, or larger than, that which may result from the inclusion of a best estimate of that process. The ability to examine the possible consequences of adding additional processes to a simulation of yield is considered to be a useful feature of a yield predictor.

STRUCTURE OF FORCYTE-11

A major problem associated with providing a simulation model with a wide variety of capabilities is that this may result in the model becoming very large, with all the attendant problems thereof. One solution to this problem is to break up the modelling activity into a series of smaller sub-models, and FORCYTE-11 is in fact more of a modelling framework than a single model. This framework consists of three major activities :

1, A "setup" activity, in which a series of plant growth modules and a soil process module are calibrated and their performance evaluated by means of a series of graphical output files. Each of the plant growth modules is an HB production simulator in which the effects of light competition is simulated. The tree module has capabilities that include those of most traditional HB yield simulators and of many canopy/light process models.

2, Once the performance of these models is deemed acceptable for the intended application of FORCYTE, binary output files from these setup programs are used, in conjunction with a file describing the management scenarios to be simulated, as input to the second actitity: an ecosystem management simulatiom model, MANAFOR (MANAgement of the FORest). MANAFOR simulates the effects of both light and nutrient availability on biomass production.

3, Output from MANAFOR is a series of files, collectively known as FORECAST, which are used as the input for the third, data analysis, activity. This third activity involves the choice of a variety of output formats and data analyses. If FORCYTE is implemented on a microcomputer, these analyses may involve the use of a variety of commercially-available software packages (e.g. spreadsheet or graphical packages).

This model structure assumes that a forest scientist will be involved in the setup activity, gathering calibration data and evaluating the performance of the setup modules before the MANAFOR program is used by a forest manager. The second activity level will initially involve a forest scientist in an evaluation of the veracity of the ecosystem simulations, but once the performance of MANAFOR has been deemed to be acceptable for a particular application, the model will be made available to informed forest managers. MANAFOR is intended both as a management gaming tool and as an ecosystem simulation model for a variety of research applications.

ECOLOGICAL PROCESSES AND MANAGEMENT ACTIVITIES REPRESENTED IN FORCYTE-11

Tables 1 and 2 describe the main processes and management activities represented in FORCYTE-11. Details of the representation of these processes, and of the manner in which management activities are simulated,

cannot be presented here, but are described in the FORCYTE-11 User's Manual (Kimmins and Scoullar, 1987). The reader is reminded that the user of the model controls the structural complexity and the processes to be represented in any particular application of FORCYTE. The model can be used with a single tree species, a single nutrient, and very few soil processes other than organic matter decomposition. Alternatively, it can be used with up to three species each of trees, shrubs, herbs and/or mosses, up to five nutrients (most users will probably only use two or three), and a variety of processes and management activities/natural events (Tables 1 and 2).

Table 1. Management Options in FORCYTE-11.*

Site preparation	- mechanical or fire (ploughing, broadcast burn, windrow, pile-and-burn)
Regeneration	- planting (any size/age of seedling/sapling/tree), coppice/root suckering, or natural seeding; monocultures or mixtures
Weed competition	- for light or nutrients by herbs, shrubs, or non-crop trees. Control of competition (manual or chemical)
Stand density control	- spacing or pre-commercial thinning; random or other defined spacing strategy
Thinning (commercial)	- high, low, random, or other defined thinning regime
Final harvest	- clearcut harvesting
Utilization level	- any defined proportion of any plant (or soil) component may be harvested at any time
Rotation length	- annual cropping, or short, medium or long (e.g. centuries) rotations
Fertilization	- broadcast or spot; single or multi-nutrients; inorganic or organic
Pruning	- removal of any defined proportion of live and/or dead branches
Herbivory	- e.g. insect defoliation of trees; wildlife browsing on herbs or shrubs
Fire	- prescribed stand or slash burning, or wildfire
Litter raking/slash harvest	- harvest of ectorganic layer, or of logging/thinning slash at any time. Upper soil layer(s) can also be removed

* The user decides which of these options are to be simulated, and how. Very simple or very complex scenarios can be simulated.

Table 2. Soil Processes or Management Impacts on Soil that can be Represented in FORCYTE-11.*

Organic matter decomposition, mineralization, immobilization
Humus decomposition and mineralization
Soil CEC and AEC, separately for organic matter and mineral soil
Soil sorption/desorption (e.g. of phosphorus)
Soil leaching
Soil mixing (soil animals, or mechanical mixing)
Root distribution by soil layers, according to nutrient availability
Allelopathic effects on decomposition
Organic matter substrate effects and plant effects on the ionic forms of nitrogen
Soil compaction and recovery therefrom
Soil erosion (sheet erosion, rather than mass wasting)
Denitrification (not presently operational)
Litterfall (and root mortality) inputs of organic matter and nutrients to the soil
Nutrient uptake from the soil and competition for soil nutrients by plants

* Because some of these processes may be either poorly understood or poorly documented for a particular site, the user may wish to omit any or all of them from the simulation, and can do so. However, the user is reminded that omitting the simulation of a process that is known to be important is as large an assumption as including it, and may lead to as great or even greater error than including a conservative simulation of the process.

APPLICATION AND IMPLEMENTATION OF FORCYTE-11

FORCYTE-11 was developed for use primarily in forest management and research, but because it is an ecosystem model, it can have a variety of other applications. A tropical version has been developed for agro-forestry research in Indonesia, and it is planned to develop the model for use in temperate agriculture. With further modification, it could be used in mined-land reclamation research, and the planned development of FORCYTE-12 will permit future use of the model in air pollution, acid rain, and "greenhouse effect" research.

Within forestry, the model is being modified to improve its temporal resolution of the processes in the early stages of stand establishment, especially competition for nutrients, light and moisture, but also antagonistic effects such as allelopathy. Research is under way to provide calibration and validation data to prepare and test the model for use in early succession and vegetation management research.

Because FORCYTE was developed as a management tool, it conducts economic, energy efficiency and manpower requirement analyses as well as biomass production and yield analyses. The optimum use of the model is in ranking the performance of a wide variety of alternative, stand-level, crop management strategies, and this ranking can be done on the basis of

production, yield, economics, energy and/or manpower requirements, or on the sustainability of soil fertility and ecosystem productivity. Because such applications of the model involve repeated runs and very large quantities of optional output, a supervisory software package PROBE (Apps et al., this volume) has been developed. PROBE facilitates management gaming and sensitivity analyses of the model, as well as management of the output of multiple runs in conjunction with spreadsheet software packages such as SYMPHONY (TM Lotus Corp.).

With the improvement in computer hardware, FORCYTE (which was until recently a "mainframe" model) can now be implemented on microcomputers. FORCYTE-10 can be run on a standard 640k IBM PC, XT, AT (or compatible) equipped with a math coprocessor. FORCYTE-11 currently runs on any of these microcomputers if they are equipped with a 32-bit coprocessor (e.g. a Definicon DSI-32 board).

TROPICAL AGROFORESTRY APPLICATION OF FORCYTE-11 AS AN EXAMPLE OF THE MODEL'S CAPABILITIES

Although FORCYTE-10 has been, or currently is being, tested in plantation forestry in New Zealand, Brazil, South Africa, U.S., Canada, and Scandinavia, FORCYTE-11 has not yet been field-tested. Work is currently underway to calibrate and test it in these and other locations, but its first operational test will be in the simulation of an agroforestry system in Indonesia. This tropical agroforestry application of FORCYTE-11 provides a good example of the planned capabilities of this version of the model for when it is used in plantation forestry applications.

Large numbers of rural people in western Java depend upon a subsistence agroforestry cropping system on upland areas which have relatively poor soils. The "talun-kebun" system that they use has apparently provided a sustained supply of food and wood products for many generations (and probably many centuries) with very little external inputs of nutrients to maintain soil fertility (Christanty and Kimmins, mss in preparation[1]). However, a growing desire for cash crops is resulting in changes in this traditional method of land use, and there is growing concern about soil impoverishment and soil erosion.

The talun-kebun system consists of a six-to-seven-year management cycle in which stands of perennial clump bamboo are periodically clearcut and the area ("field") used for growing food crops for two years before being allowed to return to a four-to-five-year fallow period of bamboo. Clearcutting, raking the forest floor and slash into piles for burning, and hoeing the soil to a depth of 25 cm (thereby killing about 20t ha^{-1} of fine bamboo roots) reduces the vigour of the bamboo to the point at which it poses no competitive threat to the planted food crops in the first year. These crops are (typically) cucumber, bitter solanum and hyacinth (pole) beans. Ash from the burned slash piles, plus some animal manure and an application of NPK fertilizer, are used to increase the

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[1] Based on L. Christanty's Ph.D. thesis at the Univ. of B.C. (in preparation).

production of these vegetables. In spite of these nutrient additions, the fertility of the upper soil layers declines during the first year, and the field is planted to cassava (a less nutrient-demanding root-crop) for the second year after clearcutting. During this second year, the bamboo has recovered some of its vigour and has progressed from the "grass" stage to the production of small (1-2m tall) culms (aerial shoots). Because these culms pose increasing competition for light, and because of below-ground competition from the increasing biomass of bamboo fine roots, the field is abandoned after two years and permitted to revert to an unmanaged stand of bamboo. The bamboo clumps produce successively taller culms and, because of the high silica content of the above-ground litterfall, a relatively slowly decomposing ectorganic layer (forest floor). Once this layer has accumulated to a certain depth, and the upper soil has become darkened with the accumulating humus, the bamboo is again clearcut and the cycle repeated.

The sustainability of the system appears to be based largely on the "nutrient pumping" action of the bamboo, the slow decomposition of its silica-rich litter, and the extremely high biomass of bamboo fine roots. The bamboo recovers much of the nutrients leached deeper into the soil profile during the two years of cropping and deposits them at or near the soil surface as above-ground litter and dead fine roots. This action is reflected in the rural farmer's saying: "without bamboo, the land dies".

FORCYTE-11 has been designed so that it can be used to perform simulation experiments on the possible consequences of changes in this traditional land use system. This requires the simulation of the growth of several different herbaceous food crop species and of bamboo, the harvesting of economic components of the biomass, the addition of ash, manure and fertilizers, the leaching and erosion of nutrients, the loss of nutrients in smoke, the addition of symbiotically-fixed nitrogen by the hyacinth beans and scattered Albizzia trees, the composting of food crop wastes and spreading of compost, the mixing of soil by soil animals and hoeing, the leaching of nutrients down through the soil, and various cultural activities associated with the management cycle. Nutrient and light competition must be simulated. Ideally, the spatial relationships of the clump bamboo and the interplanted food crops should be represented, but this must await the addition of a horizontal spatial representation of plants in FORYTE-12.

Simulation of the Javanese talun-kebun system demonstrates the potential of this modelling approach for research on and/or management gaming with conventional or innovative forestry, agroforestry, or agricultural cropping systems. The capability to simulate this tropical land use system confers on the model the ability to represent a wide variety of non-tropical silvicultural/agricultural systems.

FUTURE DEVELOPMENT AND AVAILABILITY OF THE MODEL

As already noted, several further developments of FORCYTE are planned. An explicit simulation of temperature and moisture determinants of growth and a spatial representation of individual trees and other plants will be provided in FORCYTE-12. The stand-level FORCYTE-11 and -12 will be linked up with a GIS and/or whole-forest management model to provide an improved

basis for timber supply and regional economic modelling. It is also hoped to make the necessary modifications to render the model suitable for acid rain, greenhouse effect, and disturbed land reclamation research.

FORCYTE-10 is, and FORCYTE-11 soon will be, available through the Canadian Forestry Service's National Forestry Institute at Petawawa, Ontario. Any readers interested in the model may refer to the list of references appended or may contact the senior author.

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PARAMETER ESTIMATION AND TESTING OF A PROCESS-BASED STAND GROWTH MODEL USING MONTE CARLO TECHNIQUES

Annikki Mäkelä

ABSTRACT. This paper reports the testing and calibration of a carbon-balance model of tree growth. Partitioning of growth is performed according to the principle of functional balance and the pipe-model theory. A simple stand-level version of the model is presented, and the results are compared with growth and yield tables. The analysis applies a generalised sensitivity test employing Monte Carlo techniques.

INTRODUCTION

Recent advances in forest growth and yield modelling have indicated the high potential of process-oriented models for examining a variety of questions ranging from standard management problems to more complex issues of environmental change (Botkin et al., 1972; Ek and Dudek, 1980; West et al., 1980; Shugart, 1984; Mäkelä, 1986; Valentine; 1987). Yet to date, owing to a number of practical difficulties, their use has been rather limited. For example, there is uncertainty about model structure due to a lack of some basic eco-physiological knowledge, while model validation faces problems of inaccurate and insufficient data.

One of the major problems of model structure is related to the allocation of growth resources within individual trees. A number of mechanisms have been suggested, but as yet no conventional practice has emerged. The models proposed include temporally constant coefficients (Mäkelä and Hari, 1986), allometric ratios (e.g. Shugart, 1984), and acclimative strategies such as the priority principle (Bossel, 1986). A recent approach that has proved promising, at least in qualitative individual-tree studies, applies the pipe-model theory (Shinozaki et al., 1964 a,b) to combine characteristics of both allometric ratios and acclimative strategies (Valentine, 1985; Mäkelä, 1986).

The problems of model verification and calibration are related to the fact that many of the parameters and state variables, despite their sound eco-physiological definitions, are difficult if not impossible to measure with current techniques. One solution, of course, would be to relax the requirement for the parameter values to be physically meaningful and revert to more conventional statistical procedures; whereupon, however, the causal implications of the model structure would be obscured. Therefore, from the perspective of model verification, it would be more useful if we could fully utilize whatever data are at hand, and furthermore, identify the missing data most likely to provide a stringent test of the model when made available. Answering these questions has been the objective in recent applications of Monte Carlo techniques to the calibration and sensitivity analysis of complex models with input and output uncertainty (Spear and Hornberger, 1978; Hornberger and Cosby, 1985).

This paper reports the testing and calibration of the pipe-model based allocation pattern (Mäkelä, 1986) against stand-level growth data, using the above-mentioned Monte Carlo techniques. While the focus of the report is on model validity, it also aims at illustrating the method, which so far has received little attention in forestry applications.

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THE MODEL

INDIVIDUAL TREE MODEL

The model presented by Mäkelä (1986) calculates total annual tree growth on the basis of photosynthesis and respiration and allocates this to the biomass compartments according to a scheme derived from: (1) the principle of functional balance (White, 1935; Brouwer, 1962) and (2) the pipe-model theory (Shinozaki et al., 1964 a,b). Partitioning coefficients, defined as the proportional share of total growth attributable to each biomass compartment, are derived for five state variables comprising foliage, feeder roots, stem, branches, and transport roots. Partitioning between diameter and length growth in the woody organs is not calculated, rather the model assumes independent input in the form of the average lengths of sapwood 'pipes' in the stem, branches and transport roots.

In the present version of the model, we compute the average lengths from tree height, h, and length of the living crown, l. The former is an independent input function, while the latter is assumed proportional to a power of foliage biomass. The average lenghts are calculated as

$$h_s = (h-l) + \phi_s l, \; h_B = \phi_B l, \; h_c = \phi_c h \qquad (1)$$

where ϕ_s, ϕ_B and ϕ_c are coefficients related to tree form.

In order to compare model results with standard forestry data, we include basal area among the state variables by assuming that basal area growth is equal to the gross growth of the sapwood area of the stem.

PHOTOSYNTHESIS IN THE CANOPY

When applied at the stand level, the individual tree model has to be supplied with a description of stand interactions. Presently, we only consider shading, adopting the approach of Mäkelä and Hari (1986). They assume that the stand is horizontally homogeneous, and compute the effect of shading on photosynthesis, f(x), at the horizontal layer x. This depends on the shading biomass at x, B(x), defined as the foliage biomass per unit area above the horizontal layer x. The relationship is determined using the following empirical function

$$f(x) = (1 + \exp(-2(\log B - a_f)/b_f))^{-1} \qquad (2)$$

where a_f and b_f are parameters. The whole-tree average photosynthetic rate is obtained by integration over the crown, assuming that needle biomass is evenly distributed between tree height and crown base.

STAND GROWTH

A rigorous approach to stand growth would start off with individual trees of various sizes, account for their interactions, and include the self-thinning of the stand as a function of suppression and stochastic damages (e.g. Shugart, 1984; Mäkelä and Hari, 1986). However, since the present focus is on testing the individual tree allocation pattern, we would like to minimize the number of additional assumptions and keep the structure of the stand model as simple as possible. To do so, we shall consider the possibility of simply describing the stand in terms of a suitably chosen average tree.

Such an approach is adequate for the present purpose if the average tree fulfils the following conditions:

(1) in any one year, the state of the stand can be derived from the state of the average tree and stand density
(2) in any one year, the allocation of growth resources in the stand can be derived from that in the average tree, and stand density
(3) after the transfer of state from year to year, the subject tree retains its average character

It can be shown that if we define the average tree as one with basal area, B, equal to stand average, and height, h, equal to the average weighted with respect to basal area, the above requirements (1) and (2) will be met provided that certain additional conditions hold. In particular, we have to assume that (1) the basal area:sapwood area ratio, and (2) the form factor, volume/Bh, are constant throughout the stand in any one year.

Let us now turn to requirement (3). The key issue here is that the average size of the stand generally increases due to self-thinning because the dying trees are smaller than the surviving trees. This has to be incorporated as an additional, non-metabolic part in the growth of the average tree (Valentine, 1987).

Denote the density of the stand in the year k by N, and assume that N_D will die and N_S survive in that year. Assume, further, that the average basal area and height are known for the dying population as a function of those in the original population:

$$B_D = \Psi_B B \quad , \quad h_D = \Psi_H h \tag{3}$$

where $0 < \Psi_B < 1$, $0 < \Psi_H < 1$. It is then a simple calculation to show that the corresponding averages for the survivors are

$$B_S = (1 + N_D(1 - \Psi_B)/N_S)\ B \quad , \qquad h_S = \frac{N_S + N_D(1 - \Psi_B \Psi_H)}{N_S + N_D(1 - \Psi_B)}\ h$$

Under the above assumptions of constant basal area: sapwood area ratio and form factor, this allows us to determine the corresponding survivor average values for all state variables.

SUMMARY OF THE MODEL

The model derived above presents the growth of an even-aged Scots pine stand in the environmental conditions specified by its parameters and input functions. It has six state variables and four input functions, summarized in Table 1, and 23 parameters, listed in Table 2.

Table 1. State and input variables.

State variables		Input functions	
foliage biomass	W	height	h
feeder root biomass	W	stand density	N
branch biomass	W	diversity coefficient, height	Ψ_H
stem biomass/volume	W / V	diversity coefficient, basal area	Ψ_D
transport root biomass	W		
basal area	B		

EMPIRICAL MATERIAL

PARAMETER VALUES

As the field of quantitative forest ecology is relatively young, there are few sources of data suitable for developing reliable estimates for the present parameters. The main references used in this study comprise (1) the work of a collaborative project between the Department of Silviculture , University of Helsinki, and two soviet research institutes in Estonia and Karelia (Hari et al., 1985), (2) the results of the Swedish Coniferous Forest Project (SWECON) (Persson, 1980), and (3) a study of the nutrient budget of three pine stands in Southern Finland (Mälkönen, 1974). All these studies concern Pinus sylvestris growing on fairly dry and poor, sandy podsol soils under climatic conditions comparable to those prevailing in Southern Finland, and most of the stands considered are of the Vaccinium type (VT) (Cajander's (1949) classification).

Column 5 in Table 2 shows estimated plausible ranges for the parameters. The width of the range reflects the uncertainty related to the parameter value.

As regards other site types and climatic regions, the information available appears considerably sparser. However, we do have a qualitative understanding of the directions of change of some of the paramters as a function of climate and site type. This is particularly true of the metabolic parameters, whereas the variation of some of the structural ratios is more poorly understood.

Table 2. Parameters.

	Symbol	Definition	Unit	Range
1	σ_c	specific photosynthetic rate	kg C/kg DW/yr	1.25 - 3.33
2	r_s	specific maintenance respiration of sapwood	kg C/kg DW/yr	0.004 - 0.040
3	r_p	specific maintenance respiration; foliage, roots	kg C/kg DW/yr	0.025 - 0.130
4	r_g	specific growth respiration	kg C/kg DW	0.0 - 0.3
5	σ_N	root-specific nitrogen uptake rate	kg N/kg DW/yr	0.005 - 0.06
6	f_c	carbon content of dry matter	kg C/kg DW	0.5
7	π_N	nitrogen:carbon ratio of dry weight	kg N/kg C	0.005 - 0.015
8	η_s	foliage-dry-weight:stem-sapwood ratio	kg DW/m² SW	480 - 520
9	η_B	foliage-dry-weight:branch-sapwood ratio	kg DW/m² SW	440 - 460
10	η_t	foliage-dry-weight:transport-root-sapwood ratio	kg DW/m² SW	2300 - 2500
11	ρ	wood density	kg DW/m³ DW	380 - 420
12	ϕ_s	form coefficient of stem	unitless	0.4 - 0.5
13	ϕ_B	form coefficient of branch system	unitless	0.3 - 0.5
14	ϕ_t	form coefficient of transport roots	unitless	0.4 - 0.7
15	s_f	foliage-specific turnover rate	1/yr	0.2 - 0.3
16	s_r	root-specific turnover rate	1/yr	0.5 - 1.2
17	s_B	specific turnover rate; branches, transport roots	1/yr	0.05 - 0.15
18	d_s	sapwood-area specific turnover rate; stem	1/yr	0.01 - 0.07
19	d_B	sapwood-area specific turnover rate; branches, roots	1/yr	0.01 - 0.07
20	a	coefficient: crown length and foliage biomass	m/kg$^{1/2}$	2.5 - 3.5
21	p	exponent: crown length and foliage biomass	unitless	0.4 - 0.6
22	a_1	coefficient in shading function (eqn. 2)	log(kg/ha)	3.3 - 3.9
23	b_1	coefficient in shading function (eqn. 2)	log(kg/ha)	-0.8 - -0.25

STAND DEVELOPMENT

The growth and yield tables collected by foresters over the years are perhaps still the most concise and reliable source of data available on the development of forest stands in different climatic regions and growing sites. For example, the tables used in Finland cover two of the four input functions of the model, average tree height and stand density, and two of the six state variables, stem volume and average basal area. Additionally, dominant height is documented. (Koivisto, 1959).

As regards the rest of the state variables , few long-term data compatible with the growth and yield tables are available. For North European conditions, perhaps the best estimates are those published by the SWECON project (Albrektson, 1980). These comprise the long-term

development of stand biomass in five compartments, based on 12 sites of different ages in Southern Sweden. Most of the sites appear to be comparable with the VT site. The results are in fairly good agreement with some point values reported in other studies (Mälkönen, 1974; Hari *et al*., 1985).

CONCLUSIONS: PERFORMANCE CRITERIA

The requirement that model output is in agreement with observation can be expressed in many ways. In this study, the key criterium is that the calculated diameter of the average tree, D, is within a range of $\pm$ 10% from the observed, D , at every moment of observation. Since volume growth is a function of height and diameter growth, if the model is adequate, the validity of stand volume follows from that of diameter.

Owing to the difficulties of combining different data sets rigorously, the information concerning the other state variables will only be used as a check of the order of magnitude of model output. In particular, we require that at any moment of time, needle biomass be no less than the overall minimum observed.

ANALYSIS OF PERFORMANCE

Spear, Hornberger and co-workers (e.g. Spear and Hornberger, 1978; Hornberger and Cosby, 1985) have developed the stochastic method applied here for the testing, sensitivity analysis and calibration of simulation models with a complex structure and sparse data. The method is based on Monte Carlo simulations, the skeleton of which is to draw a parameter vector **p** randomly from some *a priori* distributions, run the model with **p** as an input, store the result, and repeat the procedure N times. In this case, the result stored consists of the parameter vector, model output, and performance classification.

The test of the model is based on the observation that if a subset of the *a priori* parameter set exists which gives rise to the accepted performance, this will become apparent in a finite number of Monte Carlo simulations. Once this has been established, the objective of the rest of the procedure is to identify those parameters that are the most significant in separating the accepted from the rejected performance, and that part of the original parameter space that is the most likely to yield accepted performance exclusively. This is done by analysing the accepted and rejected parameter sets statistically.

The analysis proceeds in two steps. First, we examine to what extent each of the parameters alone explains the performance classification. If a parameter is not important in distinguishing between the accepted and rejected performance, the distributions of the accepted and rejected parameter values will be equal. Conversely, the more significant a parameter is, the more the two distributions differ. A sensitivity ranking of the parameters can hence be based upon a measure of the separation of the cumulative distributions of the accepted and rejected parameter sets. Following Hornberger and Cosby (1985), we use the Kolmogorov-Smirnov two-sample test in this study.

Separation between the accepted and rejected parameter distributions is sufficient but not necessary for indicating high sensitivity. If there are mutual correlations in the accepted set, the correlated parameters may not separate under the performance classification, yet a combination of these may be essential in determining acceptance. Therefore, the second step of the procedure analyses the correlation structures imposed by the performance classification, with the objective of extracting the important combinations. Spear and Hornberger (1978) propose to do this by means of principal components analysis; this study, however, applies the less systematic method of multiple linear regression.

RESULTS AND DISCUSSION

The Monte Carlo simulations were carried out for the VT growing site. Altogether 22 parameters were varied stochastically in each run. These comprise 19 of the original parameters, two coefficients allowing variation in the initial state, and one parameter related to the input functions. Four of the original parameters, i.e. r_g, f_c, π_w, and ρ, were set constant, owing to the fact that they only occur as multipliers of certain other parameters, wherein their uncertainties could be embedded.

The initial state of stem volume and diameter were set equal to the first tabulated data point, and the initial values of the other state variables were chosen to be consistent with these data and model assumptions. In accordance with the performance criteria, the initial diameter was allowed to vary ± 10% around the tabulated value (parameter 24). The initial value of needle biomass followed this variation, with an additional uncertainty range of ± 2% (parameter 25).

The tabulated values were used for the input functions h(t) and N(t). The function $\Psi_M(t)$ was approximated from the difference between average and dominant height, with p as a stochastic parameter (parameter 26):

$$\Psi_M(t) = p \;\; (h_D(t) - h(t)) \;/\; h(t) \qquad (4)$$

and the function $\Psi_B(t)$ was simply set equal to Ψ_M^2. Linear interpolation was used to estimate annual values for the input functions from values tabulated at 5-year intervals.

A statistical analysis of the Monte Carlo simulations is shown in Table 3. Columns 2 and 3 show the initial ranges assigned to the parameters, and columns 4 and 5 give the normalized average and variance of the accepted parameters in the first simulation. The normalization gives zero mean and unit variance for uniform distribution. Column 6 details the results of the Kolmogorov-Smirnov test for the first run, the asterixes indicating the levels of confidence (0.95, 0.99 and 0.999) with which the null hypothesis (of no significant difference between the rejected and accepted sets) can be rejected. The most significant parameters determining performance were: (1) those related to the photosynthetic light ratio, a_1 and b_n (2) the initial diameter, (3), sapwood specific maintenance respiration, r_s, (4) turnover rate of stem sapwood, d_s, (5) specific photosynthetic rate, σ_c, and (6) turnover rate of branch sapwood, d_B. The acceptance rate in the first simulation was only 0.3%.

Table 3. Results of the Monte Carlo simulations

parameter	initial distribution min	initial distribution max	normalized average	normalized variance	Kolmogorov-Smirnov test	final distribution min	final distribution max	comparison with initial %	rank
1 *	1.25	3.33	-0.236	0.837	0.182 ***	1.80	2.30	24	4
2 *	0.004	0.04	-0.811	0.508	0.382 ***	0.004	0.012	22	3
3 *	0.025	0.130	0.083	0.931	0.061	0.025	0.13	100	
5 *	0.005	0.06	-0.137	0.973	0.108 **	0.02	0.05	55	7
8	480.	520.	-0.029	0.979	0.056	480	520	100	
9	440.	460.	0.048	1.058	0.081	440	460	100	
10 *	2300.	2500.	-0.030	0.950	0.067	2300	2500	100	
12	0.38	0.63	0.050	1.094	0.062	0.38	0.63	100	
13	0.285	0.525	0.072	0.954	0.063	0.285	0.525	100	
14	0.38	0.735	-0.123	1.081	0.091 *	0.38	0.735	100	
15	0.20	0.30	0.195	0.984	0.113 **	0.20	0.30	100	
16 *	0.50	1.20	-0.025	0.977	0.054	0.50	1.20	100	
17	0.05	0.15	-0.113	0.945	0.085	0.05	0.15	100	
18	0.01	0.07	-0.137	0.338	0.246 ***	0.033	0.045	20	2
19 *	0.01	0.07	-0.275	1.005	0.136 ***	0.01	0.07	100	
20	2.5	3.5	0.078	0.977	0.079	2.50	3.50	100	
21 *	0.4	0.6	0.096	0.917	0.060	0.40	0.60	100	
22	3.30	3.90	-0.914	0.414	0.442 ***	3.3	3.45	25	5
23 *	-.80	-.25	0.498	0.998	0.247 ***	-0.35	-0.25	18	1
24	-.10	0.10	-0.778	0.386	0.369 ***	-0.10	-0.04	30	6
25	-.02	0.02	-0.003	0.964	0.049	-0.02	0.02	100	
26 *	0.8	1.2	0.037	1.031	0.050	0.80	1.20	100	

*) inter-correlated parameters

The parameter ranges were contracted in the direction indicated by the results, and new Monte Carlo simulations were conducted, until no highly significant differences were detectable between the accepted and rejected parameter sets. These final ranges are shown in columns 7 and 8 of Table 3. The final:initial range ratio was computed, giving a sensitivity ranking similar to the Kolmogorov-Smirnov test.

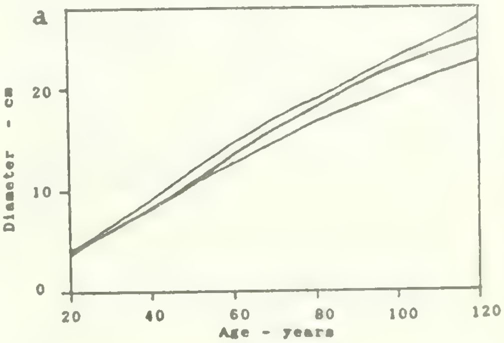
The final parameter ranges resulted in a 45% acceptance of all runs, indicating some significant correlations in the accepted parameter set. Upon inspection of the correlation matrix it was found that the shading parameter, a_r, was strongly correlated with 9 other parameters, marked with an asterix in Table 3. A multiple regression analysis showed that these correlations explained ca. 40% of the variation in a_r. When implementing the regression into the stochastic parameter input, the acceptance rate went up to 80%.

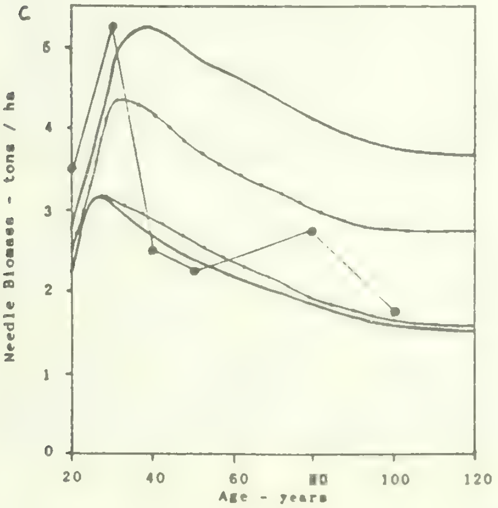
Figure 1 illustrates the development of some of the state variables in the accepted runs. Figure 1a depicts the range of the diameter of the average tree in the accepted runs of the first Monte Carlo simulation, in comparison with data (Koivisto, 1959). The result was almost identical after accounting for the cross-correlations. Figures 1b and 1c illustrate the development of volume and needle biomass, respectively.

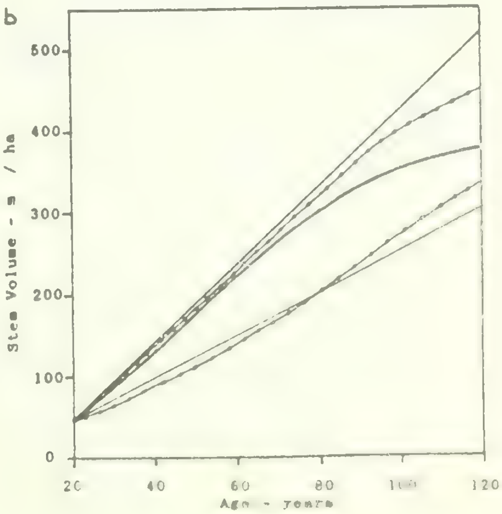
The accepted simulations fail to reproduce the decline of volume growth towards the end of the rotation, the change in stand volume more closely resembling a linear function of time. The fact that the same trend seems less pronounced in the diameter indicates that the model fails to account for some changes in the form factor over time, probably related to allocation of growth between branches and stem.

Figure 1.(a) Range of diameter development in the first Monte Carlo run compared with data (Koivisto, 1959) (middle line)
(b) Ranges of volume development in the first and the final simulations compared with data (Koivisto, 1959)
(c) Ranges of needle biomass development in the first and final simulations compared with data (Albrektson 1980)

first ,final simulation
Koivisto (1959)
Albrektson (1980)







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A GEOMETRIC MODEL OF SUNLIGHT PENETRATION FOR SLASH PINE IN NORTHERN FLORIDA

Kevin S. McKelvey[1]

ABSTRACT. Highly irregular canopies of a 20-year-old slash pine (Pinus elliottii) plantation were modeled by placing spherical envelopes representing individual needle clusters in a finite array. Needle clusters were placed randomly into the array with the distribution weighted to mimic the actual foliage distribution patterns. Ten to 12 trees were modeled in this manner. Shade patterns were then computed for a single target tree, which was positioned to eliminate boundary effects. Several simulations were performed to generalize the light penetration patterns. Two tree configurations were simulated, one in which the rows of trees were aligned with the sun azimuth to maximize the light penetration between rows, and one in which the trees were offset to negate row effects. These patterns represent unrealistic extremes and are presented for comparison. Penetration patterns of beam radiation show lower canopy levels are heavily shaded at lower sun angles of elevation. This effect is due to competitive shading from adjacent trees and is not observed at sun angles of greater than 60 degrees. Shading in the upper 2-3 meters of the crown is low regardless of sun angle. This pattern suggests that the conic crown form common to conifers allows lower foliage access to unobstructed beam radiation during certain times of the year and unobstructed diffuse sky radiation on a continuous basis. Classic exponential decline of light with canopy depth is, therefore, only anticipated for low sun angles of elevation.

INTRODUCTION

Parallel monochromatic radiation passing through a homogenous medium decreases in flux density,as described by Bouguer's (or Beer's) law:

$$I_i = I_o e^{-kz} \tag{1}$$

where Ii is the flux density at a point i, Io is the flux density above the medium, z is the distance that the beam has travelled in the medium, and k is the extinction coefficient. This simple formula lies at the heart of virtually every canopy interception model. The differences between models lie in the definition of the domain over which this formula is considered to be valid. The important requirement of this equation is the homogeneity of the medium. In the case of tree canopies, the requirement is that the leaf area be homogeneously distributed. In simple closed canopies of uniform height, it may be possible to assume

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general homogeneity of leaf area and to use a single equation to describe the entire canopy (Campbell, 1977; Halldin et al., 1979; Lemeur et al., 1979; McMurtrie et al., 1986).

In discontinuous or irregular canopies, the assumption of general homogeneity cannot be supported. The canopy is commonly truncated into various sub-canopies and equation (1) is assumed to be valid for each of the sub-canopies. These sub-canopies are usually defined as individual plants (Mann et al., 1979; Mann et al., 1980; Norman and Welles, 1983; Whitfield, 1986) or sometimes hedgerows (Charles-Edwards and Thorpe, 1976). This type of modeling is called envelope modeling because the leaf area of each sub-canopy is strictly confined to an "envelope" which is usually defined as an ellipsoid of rotation. This technique allows a great deal of flexibility in canopy modeling, because each envelope can have its own properties and envelopes can even be nested inside one another to simulate foliated and non-foliated portions of a plant (Norman and Welles, 1983). To determine shading effects, series of lines are shot through the array of envelopes and z is computed for each line as the sum of the chords created by the intersection of the line and the envelopes (Norman and Welles, 1983). The main problem with these models is the computational expense required to obtain z in complex canopies.

The canopy structure of plantation slash pine is very irregular. The trees themselves approximate cones and the foliage is arrayed around the exterior of the conic volume in a layer that becomes thinner with increasing canopy depth (Figure 1). Within this general crown form, the needles are densely clustered leaving large gaps in the canopy.

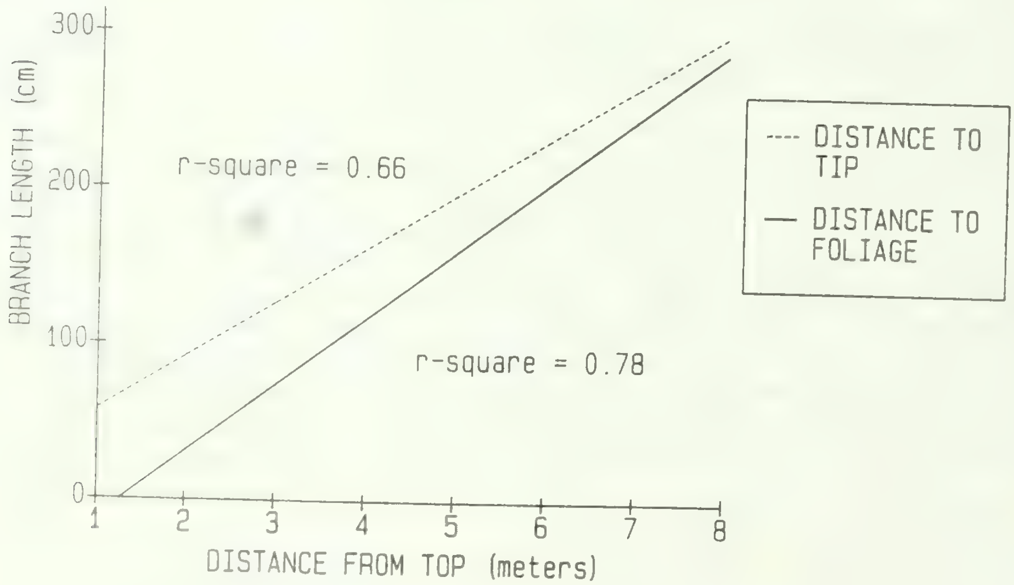

Figure 1. Total branch length and nonfoliated branch length for 20-year-old slash pine.

The model technique presented here allows realistic placement of simulated needle clusters without incurring the huge computational cost inherent in established envelope models. This model is preliminary utilization of this technique and has not been finished, tested and verified. Diffuse elements such as sky radiation, within canopy light scatter, and shading due to branches are not dealt with here. Other important parameters, such as the number of needle clusters per tree, are at this time rough estimates.

MODEL TECHNIQUES

The key to simplifying the search for shade objects in the array is to align the with the sun both in azimuth and in angle of elevation. A sun beam that enters the array at a given (x,y,z) location can then only affect those points that are identical to the entry point in two of the three dimensions. If it is passing through the array in the x direction, it can illuminate the points (x-1,y,z), (x-2,y,z)...(x-n,y,z). Shade, of course, follows the same pattern. In discrete space, possible (x,y,z) positions will be limited to the nodes of the array and the presence of shade objects over a given target node can be accomplished by a one dimensional row search

Modeling the canopy in discrete space, therefore, allows the search for potential shade to be quick and efficient. It also assures that the characteristics of shade objects that are encountered will be constant. If the distance that a sun beam travels through a shade envelope to reach a point on a target envelope is equal to X, then the distance that the beam will have to travel to pass through n shade envelopes is nX. This is true for all potential beam radiation. The computation of direct beam radiation received by any point on the target surface, therefore, can be computed from equation (1) very simply. The equation becomes:

$$Ii = Io\ e^{-kdn} \qquad (2)$$

where d is the distance traveled within a shade object and n is the number of shade objects. If patterns of shading are primarily what is desired, then light transmission can be measured at a particular reference point on all targets. In this case, d becomes constant and can be absorbed into k. Relative light density levels can be determined simply by taking the negative exponential of the number of shade objects encountered.

The sun shifts in both angle of elevation and azimuth throughout the course of the day. If one envisions the array as existing in the midst of a large stand with known spacing between trees, then rotational shifts to track the sun azimuth will be reflected in shifts of the positions of the trees inside the array. If the pivotal axis is the stem of a particular tree, then that tree will remain at a constant position in the array, and the surrounding trees will shift their positions in relation to it. By making the pivot tree the target, any sun azimuth can be simulated by simply shifting the position of the shade trees visa-vis the target. Any pattern of spacing can be used and that trees that are exterior to the array at the initial array azimuth may vary in size or shape. All that is necessary is that the distance and azimuth from the

target tree and any special characteristics of the potential shade trees be specified at the beginning of the simulation.

The technique by which azimuth is simulated can be also be utilized to simulate sun angles of elevation. In this case, the array can be imagined as a transparent cube that can be rotated vertically around the trees without affecting them. Once again this rotation represents a shift in the relative positions of the trees in the array. If the array rotates 20 degrees counter-clockwise, the trees have, in terms of their array locations, rotated 20 degrees in the opposite direction. Upon initial placement in the array, the angle and distance in relation to the center of the vertical plane in which a cluster lies is computed and stored for each occupied node. Given this information, a new position can be computed for each needle cluster at any sun angle. All positions are computed from the initial data to prevent the buildup of rounding errors during rotation.

CONSTRUCTING THE TREES

The simulated cluster size was based on the average needle length for the sampled trees (17.3 cm, s.d. = 3.36 cm). A spherical cluster that assumed the mean needle length as its radius would have a diameter is 34.6 cm. Because needles bend considerably and because the extreme periphery of the cluster has an extremely low needle density, a somewhat smaller cluster size of 25 cm was chosen. The array grid size was set equal to the cluster size. One of the main concerns in model construction was to place the clusters as accurately as possible. To accomplish this, needle clusters were first placed randomly into vertical space in proportions dictated by the distribution of foliar biomass (Figure 2). Once a vertical level was chosen, the horizontal position of each cluster was determined by creating a Cartesian plane with the "stem" of the tree at the origin. An azimuth was then chosen randomly between 0 and 2π (it was assumed that there were no density differences related to azimuth on the tree),and a distance was selected by retrieving actual branch data appropriate to that level from a random access file. The probability distribution for cluster placement within the foliated region of a limb was assumed to be uniform. The cluster was then placed into a node in the array by rounding to the nearest discrete x,y,z location. If the node was already occupied, the adjacent nodes in the plane dimension were searched randomly and the cluster was placed in the first unoccupied node that was encountered in the random walk. If no empty nodes were encountered, then a flag was sent to the screen and the placement procedure was repeated. The rationale for placement in the nearest available space was to minimize the distortion of the probability distributions in both horizontal and vertical space due to the progressive filling of the nodes in the array. The cluster placement continued until a fixed number of clusters, in this case 200, had been placed. All of the trees, therefore,had the same number of clusters and only differed due to the randomization of the system.

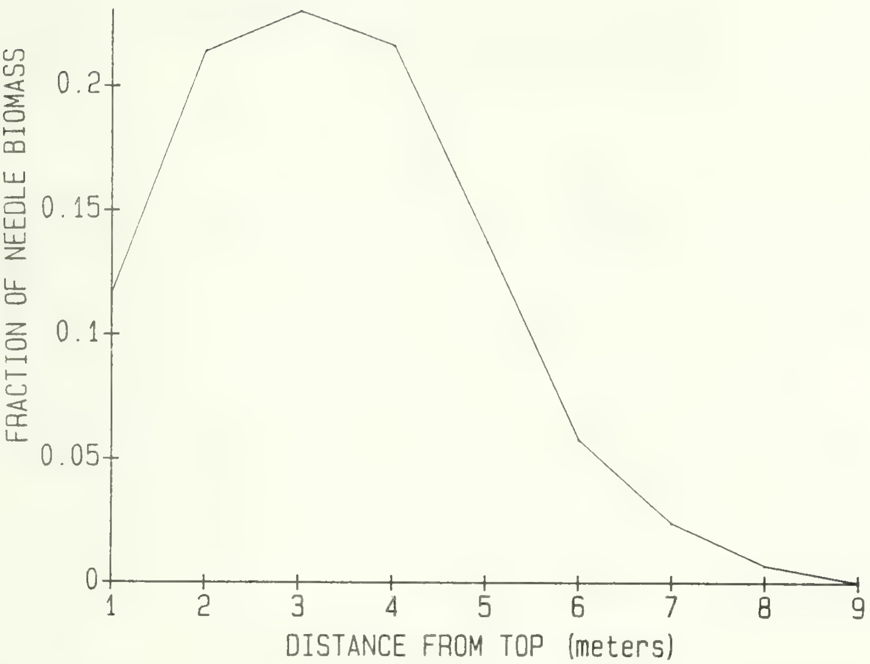

Figure 2. Needle distribution obtained through the destructive sampling of 36 trees within a 20-year-old slash pine plantation.

Trees were placed into the array assuming that, as in the plantation, they were planted in rows. An equidistant spacing of 3 meters between both the trees and the rows was assumed. This approximates the mean spacing within the plantation (2.88 meters). Two tree configurations were modeled (Figure 3). In one, tree rows were aligned with the sun azimuth. This configuration allows the maximum light to penetrate to the lower canopy levels. In the other, the rows were trees were offset in the direction of the sun azimuth. This configuration eliminates any row effect and should shade the lower levels more heavily.

ROW CONFIGURATION	OFFSET CONFIGURATION
S S S	S S
S S S	S S S
S S S	S S
S T S	S T S

Figure 3. A vertical view of the two tree spacing configurations modeled. S represents a shade tree and T the target tree.

In a model of this sort, it is important to avoid artifices created by the boundaries of the array space. Shade calculations must, therefore, be performed on a target area that is sufficiently far from a system boundary to be insulated completely from boundary effects. If the array is assumed always to be oriented with the sun azimuth, then the boundaries perpendicular to the sun azimuth need only be the maximum potential width of the target space in that dimension. In the direction of the sun, the necessary depth is a function of the crown geometry and of the sun angle of elevation. In this direction the question to be

asked is whether the nearest tree exterior to the array space could create shade on the target surface. This question can be answered precisely for any given sun angle:

$$x = y/\tan\Theta \tag{3}$$

Where x is the horizontal distance between a node on the exterior tree and the target tree, y is the vertical difference between the two nodes, and Θ is the sun angle of elevation. If the trees approximate cones and are lined up parallel to the sun azimuth, x becomes the horizontal distance from the stem of the target tree to the stem of the exterior tree minus the longest limb on the target tree, and y becomes the depth of the crown. If the exterior tree occupies any other position in relation to the sun and to the target tree, its shade influence will be decreased. This calculation, therefore, provides a safe buffer for all potential tree configurations. It should be noted that at the limit, as Θ approaches 0, x becomes infinite. Low sun angles require enormous buffers in order to be assured of no theoretical boundary effects. In practice, boundary effects should become insignificant with large buffers regardless of sun angle. The current model uses a buffer of three trees between the sun and the target tree. With a buffer of this size, theoretical boundary effects cannot occur at sun angles in excess of 31°.

RESULTS

The effect of shifting sun angle on shade patterns is dependent on canopy depth (Figures 4 and 5). The top three meters of the canopy are very insensitive to changes in sun angle. The shade observed at these levels is self-shade within the tree rather than a competitive effect between trees. In the lower canopy levels, effects of competitive shading are strongly felt at low sun angles of elevation but disappear above 60 degrees. The differences between the row and the offset configurations are seen primarily at the lowest canopy levels. Lower limbs are long and can project into the inter-row areas where there is little competitive shade if the row and sun azimuth are equal. In an evenly spaced canopy this effect will be transitive and of little importance. In other configurations, such as double rows this effect is more prominent.

CONCLUSIONS

If tree crowns are modeled as discrete geometric entities, then patterns of light penetration will be dominated by the geometry of the canopies rather than by an exponential decline function. In this model, the overall conic nature of the tree canopies dominates the shade patterns. The lack of shade to the lower limbs at high sun angles is anticipated in a model that treats the foliage surface as the surface of a conic volume. The effect of overall conic tree geometry cannot, therefore, be ignored if it exists.

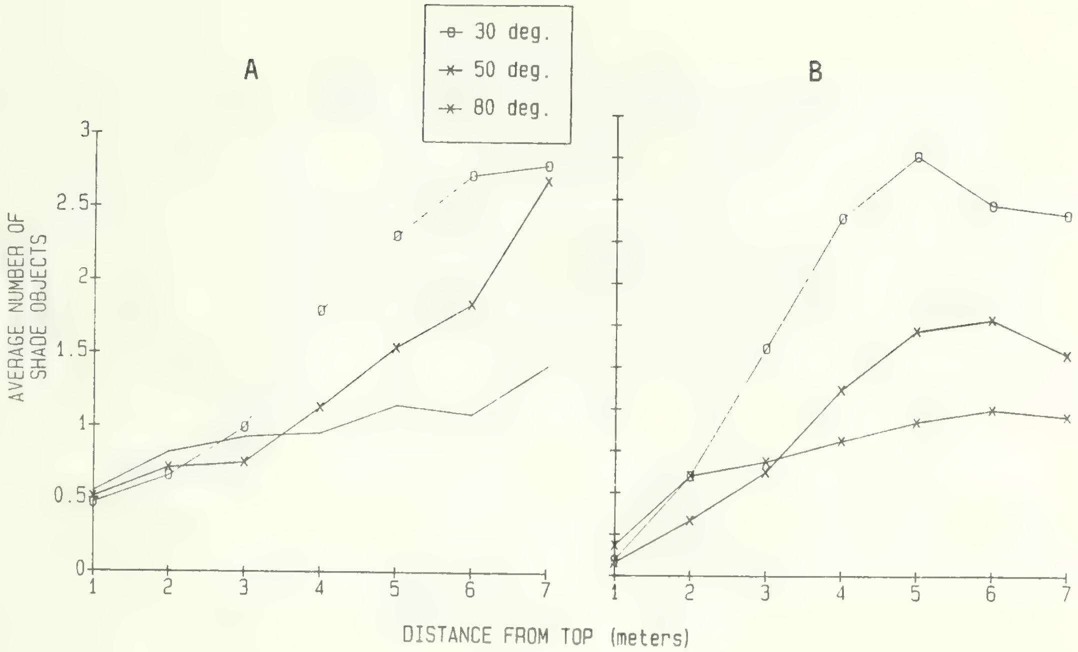

Figure 4 The average number of simulated clusters encountered in row searches for all of the canopy levels. A is the row configuration, B is the offset configuration. Values were derived from 20 simulations.

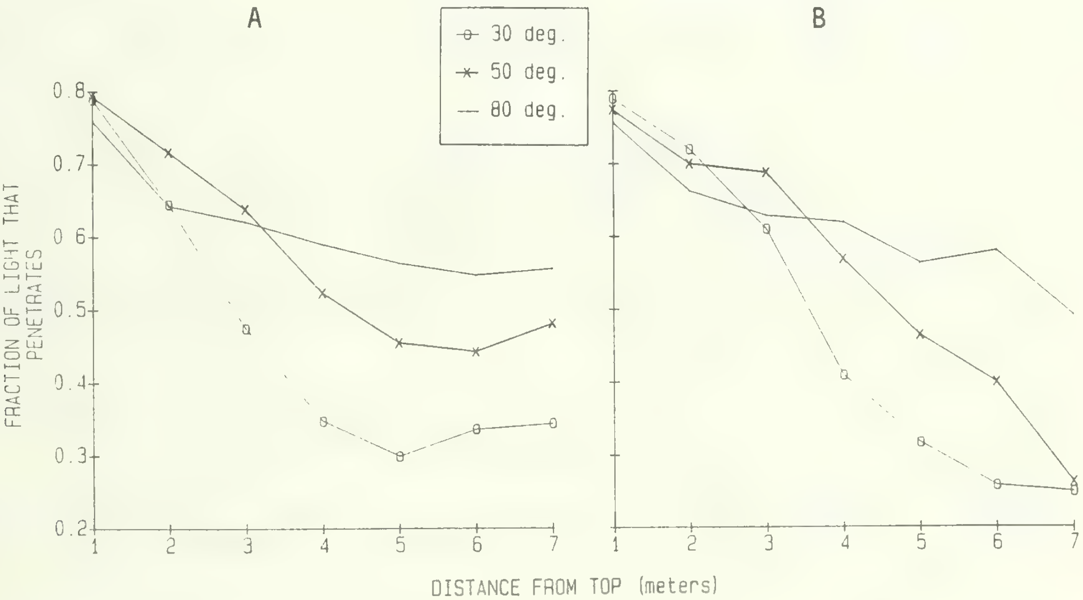

Figure 5. The average light penetration based on Figure 4. The k value (equation (2)) was arbitrarily set to 0.5. A is the row configuration, B is the offset configuration. Values were derived from 20 simulations.

The assumption of an exponential decline based on average leaf area would, in this stand, greatly underestimate the amount of beam light penetrating to the lower canopy levels at high sun angles as well as the unobserved sky radiation that will reach the lowest canopy levels throughout the day. The full potential of modeling individual needle clusters has at this time not been fully explored. The light transmission properties of needle clusters can be modeled in great detail if desired, and conic shadow effects such as spreading penumbral cones can be modeled. In general, the model appears to be a flexible basis for explorations of canopy architecture allowing a great deal of realism without extracting a prohibitive computational cost.

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SIMULATING THE INFLUENCE OF TEMPERATURE AND LIGHT ON THE GROWTH OF JUVENILE POPLARS IN THEIR ESTABLISHMENT YEAR

H. M. Rauscher[1], J. G. Isebrands[2], T. R. Crow[2], R. E. Dickson[2], D. I. Dickmann[3], and D. A. Michael[4]

ABSTRACT. An ecophysiological model, ECOPHYS, has been used to examine the influence of changes in temperature and light on the growth of a poplar clone during the establishment year. Light influenced growth more than temperature, but that the interaction of both can result in about a 50 percent increase or decline in stem biomass of individual trees from a measured "base" year. Several research hypotheses were developed that need to be experimentally tested to improve our understanding of this and other clones.

INTRODUCTION

The theoretical value of knowing quantitatively what environmental conditions different species require, and of being able to explain to what extent these requirements are met by the various climates and soils, has been appreciated for a long time (Pearson 1928). Indeed, most silvicultural practices employed by forest managers are based on physiological principles. Only recently have we arrived at a state of knowledge which permits us to formulate ecophysiological explanatory models of forest tree and stand growth (de Wit et al. 1978, Sievaenen 1983, Landsberg 1986, and Mohren 1987). Few would argue that the currently available set of ecophysiological explanatory models are better in terms of predicting tree growth than the commonly used correlative, empirical models. The point is that they can be better, and no doubt eventually will be.

Causal, explanatory ecophysiological models provide the structure to allow us to integrate in quantitative and qualitative form our scientific and heuristic knowledge about the processes that govern tree growth. Their most important use at their present stage of development is to help us clarify critical knowledge gaps and uncertainties, to formulate testable hypotheses, and to provide the means of evaluating the significance and validity of research results, old and new.

The objectives of this paper are to use a recently developed causal, explanatory ecophysiological model of Populus, ECOPHYS, to illustrate the influence of temperature and light on the growth of juvenile poplar in the establishment year, and to propose testable hypotheses based on the results of these simulations for further research.

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THE MODEL

Tree growth is a function of genetic potential interacting with the physical and biotic factors of the environment. ECOPHYS V1.2 predicts the growth of Populus deltoides Bartr. ex Marsh. x Populus nigra L. (=P. x euramericana) (Eugenei) in the establishment year (no branching), assuming that moisture and nutrients are in ample supply and with no pest or disease damage. Space restrictions in these proceedings make it necessary to limit the presentation of ECOPHYS to an overview (fig. 1). A detailed explanation is in preparation for publication elsewhere.

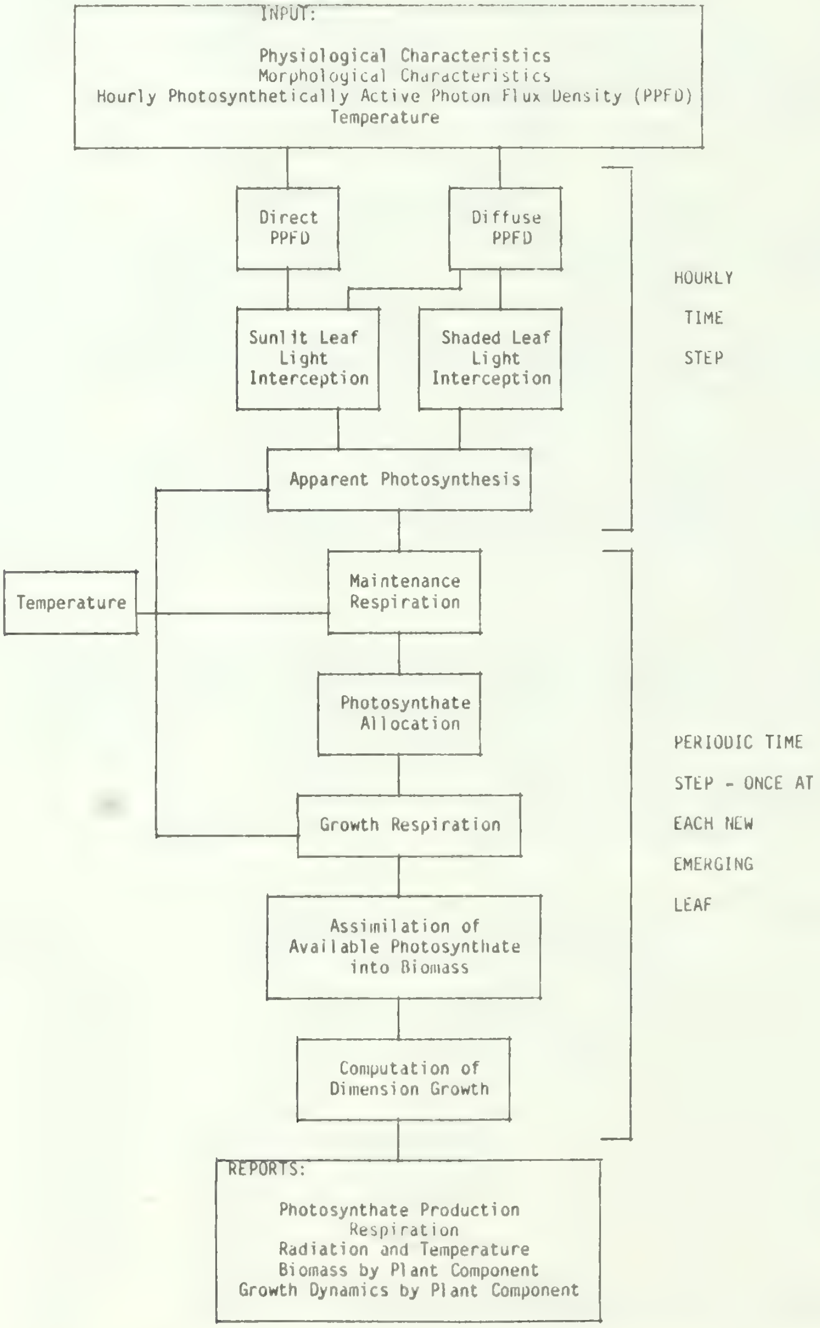

Figure 1. Schematic diagram of ECOPHYS showing general model structure.

Model Summary Description

ECOPHYS estimates (1) the hourly, daily, and seasonal photosynthate production of individual leaves; (2) the maintenance and growth respiration for each tree component; (3) the allocation of accumulated photosynthates throughout the plant; and (4) the conversion of photosynthates to biomass and dimensional growth.

Because the integrated contribution of individual leaves within a tree determines the quantity of photosynthates available for tree growth, the individual leaf was maintained as the principal biological unit in the model. The two environmental driving variables are hourly photosynthetically active photon flux density (PPFD, 400-700 nm) and hourly temperature (deg. C). Individual leaf geometry is maintained in a three-dimensional coordinate system to allow accurate calculation of mutual leaf shading. Leaf irradiance is more commonly calculated by assuming random leaf orientations, dividing the canopy into arbitrary layers, and calculating an extinction coefficient per unit leaf area penetrated (Sievaenen 1983). We chose the more rigorous geometric approach for two reasons. First, leaf orientation has been shown to greatly influence solar radiation interception and photosynthetic rates and varies among poplar clones (Isebrands and Michael 1986). It therefore seemed desirable to be able to vary leaf orientation in the model so we could investigate ways poplar can be improved through selection and breeding. Furthermore, the hourly photosynthate production time step we selected meant that the errors involved in using the average irradiance in a layer would likely be too large to yield good estimates of CO_2 uptake (Landsberg 1986).

Once leaf and shade area for each leaf has been calculated, we calculate PPFD for the shaded and unshaded regions of each leaf as a function of leaf orientation, leaf position in the crown, atmospheric attenuation of radiation, and solar position thus accounting for both direct and diffuse light. We then estimate apparent photosynthesis, a genetically dependent function (Michael et al. 1985). Apparent photosynthesis (PgA), photosynthesis estimated indirectly and uncorrected for respiration, is different for each of four age classes of poplar leaves (expanding, recently mature, mature, and over-mature). A different function is used to predict apparent photosynthesis, depending on age class. Photosynthate production is also corrected for the influence of temperature.

To calculate the amount of photosynthate available for growth, it is necessary to correct apparent photosynthesis for maintenance respiration and growth respiration. The temperature influence on respiration rates is also simulated.

PgA, adjusted for temperature and maintenance respiration, is then calculated hourly and accumulated in the leaf compartments of the model until a new leaf is due to emerge based on the estimated leaf initiation rate. Upon emergence of a new leaf, the remaining available PgA is allocated throughout the tree according to experimentally determined rates (Isebrands and Nelson 1983, Dickson 1986).

In ECOPHYS, growth is directly proportional to available photosynthates.

No empirical relationships are used to force growth to occur at a certain rate or to set lower or upper bounds to growth. Biomass accretion is simulated for the following components: immature leaves, mature leaves, immature internodes, mature internodes, cutting, large roots, and small roots. In addition, dimensional growth is computed so that leaf area, tree height, and tree diameter are estimated.

Model verification

After a model has been constructed, verification provides assurance that the model performs as intended by the developers (Nolan 1972). The objective of verification is to show that the outputs fall within the range of variation of the data used to develop it in the first place. The model has been iteratively adjusted by changing specific leaf area and specific gravity within the range of field measurements. The starting tree morphology at Julian date 204 (July 23, 1979) represented a "mean" selected from a destructive harvest of three trees occurring on that date. To form a basis for comparison, a "standard" simulation run was defined using this mean tree morphology, actual hourly PPFD and temperature measurements, and the parameter values appropriate for Eugenei. The result is that the model simulates mean response values for Eugenei for conditions measured in the 1979 growing season.

Eugenei clones were grown under a short-rotation, intensive culture (SRIC) system near Rhinelander, Wisconsin USA (45°N, 89°W) in blocks at a 0.6 m X 0.6 m spacing (Michael *et al*. In press).

Permanent plots located within the clonal block were used to study growth. Eight trees in plots distributed over the plantation were measured weekly to obtain estimates of tree height and stem diameter. Stem biomass was calculated by using H and D to estimate volume, which was then converted to stem biomass using an average specific gravity of 0.33 g/cm^3.

Simulated time series predictions between Julian date 204 and 256 (July 23-September 13, 1979) for stem dry weight, tree height, and diameter have been compared to the 8 field-grown, permanent growth plot trees measured during 1979. The coefficient of determination between measured mean value (n=8) and the simulation predicted value is 0.97 for stem dry weight, 0.98 for tree height, and 0.96 for tree diameter. Based on these results, we conclude that ECOPHYS has successfully passed the biomass and dimensional growth verification tests. Verification tests for photosynthate production and leaf area shading are still in progress.

After a model successfully passes the verification tests, it may be used with confidence to examine the impact on the system of *small* changes in one or a combination of variables. Parameter changes must be small so that the validity of the functional form is not extrapolated outside the range of the verification data.

Model validation

Validation can occur only when model outputs are compared to independently gathered measurements, the key criteria being that the

validation data must not have been used to develop or calibrate the model parameters in the first place (Nolan 1972). Neither must they have been used to formulate the functional dependencies through which the simulation model mimics the real world system. If a model is validated against several independently gathered data sets, all independent of each other, and is still found to predict well, then radical departures from the parameter values may be simulated with a higher degree of confidence that the results will be accurate.

ECOPHYS is currently undergoing its first validation test with an independently gathered data set from the University of Washington, Seattle, measured during the 1986 growing season. Another independent data set from East Lansing, Michigan, will be available at the conclusion of the 1987 growing season. Results will be reported in a subsequent paper.

Testing the effect of light and temperature changes

To examine the impact of changes in PPFD and temperature on the growth of Eugenei, we decided to exchange individual high sunlight days with low sunlight days and vice versa, 15 and 8 more sunny or cloudy days per season. Low and high temperature days for exchange were also identified (Table 1). The days chosen for the exchange had to be close to the replaced days so that the long-term seasonal trends were not disturbed. An examination of NOAA 30 year weather records for Rhinelander, Wisconsin showed that such a change in radiation and temperature regime was well within the normal range of year-to-year variation.

TABLE 1. Test conditions and results.

Test Run No.	PPFD	TEMP	Light[1/] sum (E/m^2)	Temperature[2/] sum (°C)	Above ground DM (g)	Height (cm)	Diameter (cm)
1	- 15	- 15	686	448	25	80	1.14
2	- 15	15	682	728	27	83	1.15
3	- 15	NC	682	589	27	83	1.16
4	- 8	NC	773	589	31	90	1.21
5	NC	- 15	907	448	37	101	1.25
6	NC	- 8	910	508	39	105	1.26
7 *	NC	NC	914	589	44	112	1.27
8	NC	+ 8	914	681	44	114	1.27
9	NC	+ 15	914	728	45	114	1.27
10	+ 15	- 15	1112	448	50	122	1.34
11	+ 8	NC	1031	589	51	124	1.33
12	+ 15	NC	1123	589	61	142	1.36
13	+ 15	+ 15	1128	728	66	151	1.36

1/ = Sum of Intercepted PPFD over the days 204-256.
2/ = Sum of Average Daily Temperature - 5°C over the days 204-256.
NC = No Change. * = Standard Run

RESULTS

Light-temperature impacts on growth

Holding moisture and nutrients near their optimum for Eugenei, light and temperature variations in a growing season had a direct and relatively large impact on dry matter production (table 1). Taking the extremes, test #1, representing low light and low temperatures, yielded above-ground dry matter 43 percent below that of the standard run (test #7). Test case #13, representing high light and high temperature, resulted in aboveground dry matter 50 percent above the standard run. Looking only at test runs 3, 4, 7, 11, and 12, where temperature remains constant at the standard value, plotting dry matter against the seasonal sum of intercepted PPFD (fig. 2) resulted in a monotenically increasing linear relationship. Looking only at test runs 5, 6, 7, 8, and 9, where PPFD remains constant at the standard value, and plotting dry matter against temperature (fig. 3) resulted in a asymptotic relationship. Increasing seasonal temperature sums are related to increasing dry matter production, given the standard light regime and optimum nutrients and moisture, but only up to an asymptotic value. It seems that warmer seasons tend not to increase growth, whereas cooler seasons can depress growth.

The analysis of mixed test runs 1, 2, 7, 10, and 13, where both PPFD and temperature were varied, and plot of dry matter versus PPFD and temperature (fig. 4), indicates that dry matter varies with changing light much more drastically than it does with changing temperature. In addition, at higher light levels, higher levels of temperature will increase growth more than the same levels of temperature at low light levels. There appears to be an interaction effect between temperature and light over and above the effect each has independently.

Proposed research hypotheses

We have used the model ECOPHYS, which may be regarded as a complex hypothesis in its own right, to explore the complex interactions between light, temperature, and Eugenei growth, given moisture and nutrients near optimum. This exploration has produced several insights that should be experimentally tested for validity. We present them in the form of research hypotheses:

IF moisture and nutrients are non-limiting
AND genotype and temperature are constant,
AND light interception is increased,
THEN photosynthate production increases until available CO_2 becomes limiting.

A key experimental finding in testing this hypothesis is to establish the light levels for which ambient CO_2 levels become growth-limiting. It is then of interest to explore the potential further increases possible with elevated CO_2 levels and to determine the cause of the next photosynthate production limit.

IF moisture and nutrients are non-limiting
AND photosynthate production increases,
THEN biomass increases proportionately.

Will an increase in photosynthate production always result in proportional biomass increases?

IF moisture and nutrients are non-limiting
AND genotype and light are constant,
AND temperature is increased
AND temperature is below the temperature response threshold,
THEN biomass production increases.

IF moisture and nutrients are non-limiting
AND genotype and light are constant,
AND temperature is increased
AND temperature is above the temperature response thresold,
THEN biomass production remains the same.

The key finding in this experimental test would be to find the point where additional temperature results in no significant growth increases. It would be extremely useful to observe how the genotype behaves physiologically when catabolic processes dominate. Can this understanding of the anabolic-catabolic equilibrium be used to diagnose the "health" of trees?

IF moisture and nutrients are non-limiting
AND genotype is constant,
AND light and temperature are variable,
THEN biomass accretion is a function of the feedback interaction between light and temperature.

There is an interaction between these two environmental factors that causes some compensating feedback to the growth process. The functional form of this feedback should be studied to determine whether it is additive, multiplicative, logarithmic, etc. This will provide a clue to the potential feedback interactions of other environmental factors.

CONCLUSION

An ecophysiological model, ECOPHYS, has been used to examine the influence of changes in temperature and light on the growth of a poplar clone during the establishment year. Light influenced growth more than temperature, but the interaction of both can result in about a 50 percent increase or decline in yield of individual trees from a measured "base" year. Several research hypotheses were developed that need to be experimentally tested to improve our understanding of this and other clones.

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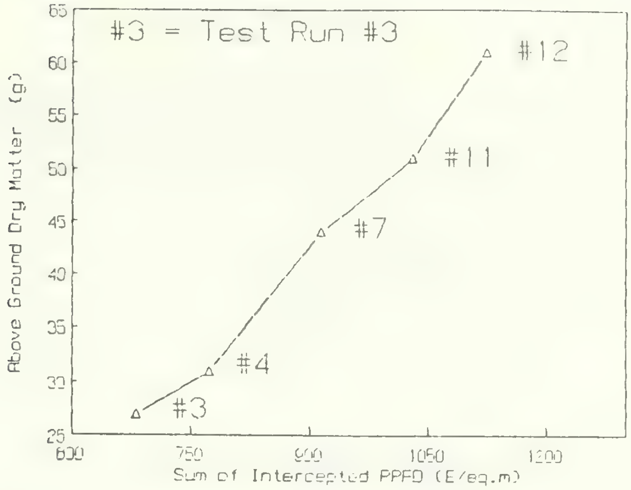

Figure 2. Test runs with temperature held constant and light varied.

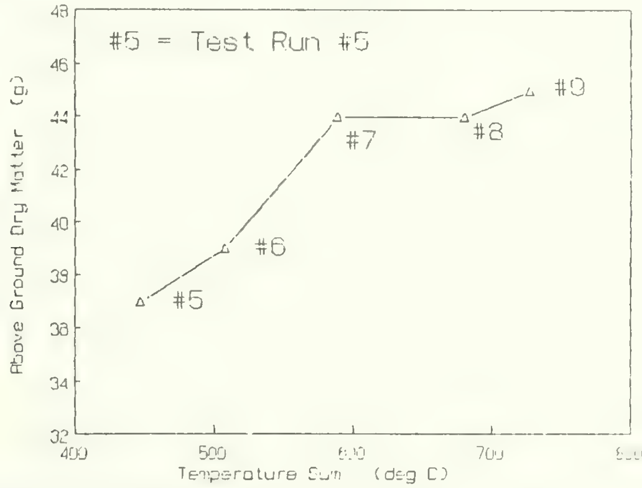

Figure 3. Test runs with light held constant and temperature varied.

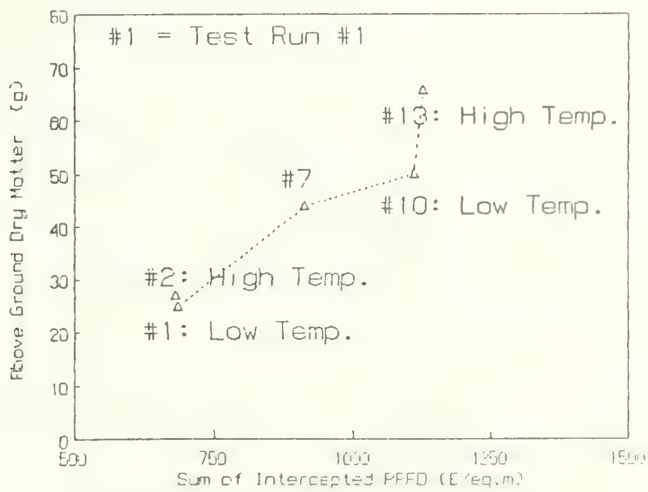

Figure 4. Test runs with both light and temperature varied simultaneously.

PROCESS MODELS FOR MONITORING FOREST HEALTH

Kurt H. Riitters[1]

ABSTRACT. Process models have been suggested as a basis for forest monitoring. A process model-based system yields biologically interpretable data according to a particular hypothesis of forest biology. But there is a potential tradeoff between the need for practicality in an operational monitoring system and the need for realism in the underlying model(s). Despite their realism, process models are sometimes viewed as impractical for monitoring because they incorporate too much detail, require too many measurements, or need better calibration. However, process models can be applied to forest health monitoring in at least three ways. An analogy with human health monitoring motivates the use of forest process models in designing a forest health monitoring system.

INTRODUCTION

The Forest Response Program of the National Acid Precipitation Assessment Program has been conducting research that could lead to a long-term forest monitoring system (NAPAP 1985; FRP 1986a). This research is targeted on the impacts of anthropogenic sulfur and nitrogen compounds that contribute to "acid rain", although other interacting air pollutants are also considered. The research and development of specific forest monitoring capabilities for NAPAP may contribute to more general monitoring systems that will be used beyond NAPAP. This paper describes how process models can aid in the design of the future system.

PROCESS MODELS FOR FOREST MONITORING?

There is a linkage between forest monitoring data and forest models that are used to interpret the data. In general, monitoring and modeling are intimately related. They are the two general methods by which future trends can be evaluated. Models and data collection systems evolve together, because modeling usually requires data, and data interpretation requires models. A forestry example of this co-evolution is the archetypal forest growth and yield model, derived from inventory data, and embodied in yield tables (e.g. McArdle et al. 1961), computer models (e.g. Belcher et al. 1982), and classical silviculture (e.g. Baker 1950). This model is conceptually derived from a traditional forest inventory hypothesis: the relationship of tree dimensions and volume to species, site quality, stocking, and age. For a new monitoring system, models can help determine the needed forest data.

The forest inventory hypothesis has been used by the Forest Response Program to investigate air pollution effects. Certain analyses of Forest

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Survey (U.S.F.S. Forest Inventory and Analysis) data have suggested a regional decline in tree growth rates (Sheffield et al. 1985). But they have not determined the cause of the apparent abnormality (Sheffield and Cost 1987), and the questions related to "acid rain" remain. Analyses of these inventory and related research plot data are appropriately made in the context of mensurational forest growth and yield models. But because those models address the forest inventory hypothesis, and are not mechanistic with respect to air pollution effects, it seems doubtful that this approach can yield a definitive statement of the roles of "acid rain" in tree growth rate reductions.

Another approach is required as a basis for monitoring when the objective is not forest inventory, because a different hypothesis is involved. Precision is not a substitute for realism. Improving the precision of inventory data will not yield different interpretive capabilities; the analysis will always be constrained to the underlying model paradigm. A more precise inventory will not necessarily provide more relevant data; a more precise model is not necessarily a more powerful interpretive tool.

Whether or not "process models"[2] are required to support forest monitoring may depend upon whether the monitoring of forest processes is required to achieve the monitoring objectives. The need for "process data" to evaluate anthropogenic impacts was emphasized in a recent workshop (Woodman 1987), and monitoring based upon similar concepts is operational in some places (e.g. NSEPB 1985). Process models will thus be needed to interpret forest monitoring data. Consistency between data and models is desirable when designing a future system, but a fully calibrated and validated model is not required to begin monitoring. In fact, such a requirement may be unduly constraining. An analogy with human health monitoring will illustrate how process models can contribute to monitoring in three ways.

A HUMAN HEALTH ANALOGY

Many consider the object of long-term monitoring to be forest "condition", perhaps including the distribution, abundance, genetic structure, or health of trees and forests (FRP 1986b). The aspect of forest condition considered here is forest health, defined as the state of a forest with respect to functioning and abnormality at a given time. Thus, forest health monitoring is the repeated measurement of the state of a forest, with interpretation with respect to functioning and abnormality. The application of health concepts to forest monitoring can be motivated by an analogy with human health systems. The three-phase analogy will be reviewed here, and the roles of process models discussed.

For humans, health is routinely monitored by reference to a few, widely-applicable, integrative indicators that have collectively come to mean "health" for medical practitioners. Examples include blood pressure

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[2]The term "process model" here refers to a model that is at least interpretable in biological terms according to a particular hypothesis of forest biology. This definition does not exclude many forest inventory models.

and body temperature. While these indicators are based on a physiological orientation towards health, it is clear that other health perspectives may provide other sets of health indicators. Any useful perspective and associated set of indicators has at least one common feature: it will detect most health abnormalities at relatively little cost. The goal of the first phase of monitoring is routine and efficient detection of possible health problems.

The goal of the second phase of health monitoring is to explain, or to interpret, any potential problems that routine monitoring has detected. When a human health problem is detected, the health professional attempts to explain the problem using a type of "covariance" analysis. In some cases, an explanation is found that does not require recourse to medical treatment, because the first phase of monitoring can accept a higher rate of false positives. But if a detected problem is otherwise inexplicable, more information may be gathered or diagnostic tests applied.

Upon diagnosis of a problem, other pertinent information is brought to bear in the third, or prognostic, phase of health monitoring. The main goal of this phase is to predict the outcome of the health problem, perhaps under different treatment scenarios. Where more than one individual is potentially affected, a population-level prognosis might include extrapolation in space as well as time. Finally, the course of the problem is followed and additional, more specific monitoring data taken, to evaluate the effects of remedial actions.

APPLICATION OF PROCESS MODELS

A fully calibrated and validated prognostic model was not required prior to initiating human health monitoring. Forest inventory was possible before computer models were developed. A similar situation may exist for forest health monitoring, where process models can be invoked in different ways in all three phases of monitoring. In the first (detective) phase, health indicators can be abstracted from any number of models to determine a set of widely-applicable measures that can be efficiently taken on a routine basis over a large population. The success of detective monitoring will depend upon a good selection of robust forest health indicators. They must be the minimally sufficient set that fully characterizes health, and they must be practical for wide application.

In the second (diagnostic) phase, insights from process models and mechanistic research can be used to develop diagnostic tests of specific causes of ill health. Only process models will incorporate the needed biological realism. The process models in this phase need to be qualitatively exact; quantification is desirable but is less important. As each new cause is discovered, a diagnostic test can be developed and applied as an adjunct, when necessary, to routine monitoring. It may also be important to monitor the changing impacts of a specific pollutant after its regulation. In that case, diagnostic monitoring could be achieved by repeated diagnostic testing. Although process models for diagnosis are much more specific than for detection, they are needed for a finite number of cases.

In the third (predictive) phase of monitoring, models are needed to

extrapolate effects over time and space, possibly under alternate regulatory or management actions. Models for this phase must be quantitatively correct, compatible with auxiliary data, and responsive to information needs. No single monitoring system can collect all needed data. Dependence upon external data sources is unavoidable, and so compatibility must be planned. Models supply quantitative information upon which decisions are based. But different decision-makers require different information in different terms, for example measures of wood volume or biodiversity. No single process model can forsee all the possibilities. Probably a series of models will be required, each building from the monitoring basis to provide information in specific terms for specific purposes.

Implementation of monitoring requires additional research, experience, knowledgeable monitors, and auxiliary information. At this time, the knowledge base of the function and normality (i.e. health) of forests is scanty. Only experience can provide the baselines by which to gauge changing health. Information about weather, pollution, and site must be taken into account, because abnormal health is a result of many natural as well as anthropogenic factors. Human intervention will continue to be essential for intelligent interpretation of monitoring data.

SUMMARY

Forest health is just one aspect of forest condition, and the Forest Response Program's monitoring project must consider the other aspects during the design and development stage. This paper has described how process models can be used to design forest health monitoring. Insights from process models can be applied, even when the modeling ideal of a fully calibrated and validated model is not available. Yet for specific cases, the modeling ideal is still a worthwhile goal.

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PARAMETER ESTIMATION IN A PHOTOSYNTHESIS-BASED GROWTH MODEL

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ABSTRACT. A growth model for an individual tree in a forest stand based on photosynthesis and respiration relationships is briefly described. Individual tree growth data (six measurements of diameter) of red pine (*Pinus resinosa* Ait.) stands are used to estimate a subset of the parameters in the model using a globally, simultaneous approach. The loss function is composed of prediction errors for individual trees at the times of measurement and is a nonlinear function of the parameters. Estimates for parameters are compared with values found in the literature. Estimation suggests ways the structure of the model should be changed. Use of alternative loss function definitions provides insight into model component stability.

INTRODUCTION

In a parameter estimation context, there are two types of forest growth models: those where the parameters have been estimated using statistical procedures to minimize the residual error in a particular data set and those which might be labeled simulation models. The parameters in simulation models are regarded as constants which can be assigned values from biometrical and physiological measurements on the basis of their definitions. Residual error minimization is not a design objective in the construction of simulation models; it is assumed that they yield qualitatively reasonable, if not accurate, results because of the sound biological bases of their construction. By definition simulation models are applicable to various growth conditions if the values for the model's constants are known for these conditions. Statistical models, in turn, produce predictions with estimable precision for the population from which the data for fitting were collected. It is usually less well known how well statistical models extrapolate to other growth conditions. Examples of statistical and simulation models are STEMS (Belcher et al. 1982) and JABOWA (Botkin et al. 1972), respectively.

In a previous paper (Sievänen et al. 1987), a forest stand growth model was described. The model is based on photosynthesis and respiration relationships (photosynthate accumulation) but predicts stand growth in terms of individual tree diameter at breast height growth. This makes it

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possible to compare the model's predictions with available, standard growth data and to fit model parameters using statistical methods. Statistical fitting of this type of model provides information about the model's structure that may aid in further development. The general suitability of this kind of model for fitting purposes can also be explored.

THE MODEL

The growth model considered here is a modification of the GROW individual tree model (Brand 1981) which contains the growth components of STEMS (Belcher et al. 1982). GROW predicts stand growth by aggregating the predicted growth of sample trees, each sample tree representing a specified number of other trees in the stand. The time step is one year. GROW was modified (Sievänen et al. 1987) so that the growth equations were based on photosynthate accumulation and relationships between tree dimensions. A brief summary of the equations is now given.[2]

The net dry weight (kg) of photosynthates formed by tree foliage (P) is assumed to be proportional to the photosynthetically active radiation (Q_f) intercepted by the subject tree:

$$P = p_0 Q_f \tag{1}$$

where p_0 is a constant and the units on Q_f are MJ. It is assumed that the stand is horizontally homogeneous and that the extinction of radiation is exponential, with extinction coefficient k for the foliage of the subject tree. The radiation intercepted by the subject tree is proportional to its contribution to the stand's ability to intercept radiation:

$$Q_f = \frac{k\ L}{KL_t}\ Q_a \tag{2}$$

where L and k are the subject tree's leaf area (m^2) and light extinction coefficient, respectively, and K and L_t are the same quantities for the section of the stand containing the tree's crown. Q_a is the amount of radiation at the subject tree's top; incident radiation for the stand was taken to be fixed at 1000 MJ/m^2 during the growing period in this study. The annual dry weight (kg) of photosynthates usable in growth is:

$$G = myP - yr(W_b + W_{sw} + W_r) \tag{3}$$

where m, y and r are constants reflecting the effects of loss of tree material, growth respiration and maintenance respiration, respectively. W_b, W_{sw} and W_r are dry weights (kg) of branches, sapwood and roots, respectively. Equation 3 is a simplified version of the corresponding equation in Sievänen et al. (1987); initial fitting results indicated the data would not support additional parameters on respiration.

The dry weights of tree components are obtained as functions of diameter (D) in cm and basal area (B) in cm^2 at breast height, tree height (H) in m and live crown ratio C. Foliage dry weight is:

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[2] Some of the equations presented here are slight modifications of those presented in Sievänen et al., 1987.

$$W_f = \frac{q}{w} C B \quad (4)$$

where w is specific leaf area and q is the slope of the linear relationship between leaf area and sapwood area in a tree. This yields:

$$L = q C B \quad (5)$$

for leaf area of the tree.

Branch dry weight is obtained from a biomass equation used by Harding and Grigal (1986) with the modification that diameter at breast height is replaced by diameter at crown base (D_b):

$$W_b = c_1 D_b^{c_2} \quad (6)$$

where c_1 and c_2 are constants. Diameter at crown base is calculated assuming that the tree bole is a cone. Stem volume (dm^3) excluding bark (V) is obtained by application of a model by Ek (1985). Using density u for the stemwood and assuming that the ratio of sapwood volume to total stem volume equals C:

$$W_s = b u V \quad \text{and} \quad W_{sw} = C W_s \quad (7)$$

where b is a correction factor for bark. Finally, it is assumed that

$$W_r = \frac{a}{S} H B \quad (8)$$

where a is a constant and S is site index, i.e., height of dominants and codominants at age 50 yrs. Tree height is expressed as a function of D based on Ek et al. (1984).

Using the above equations, changes in tree biomass and tree dimensions can be related. Further, with the aid of the same equations, all other variables in the model can be expressed as a function of basal area and crown ratio. Requiring that the annual photosynthate balance holds:

$$G = \Delta W_f + \Delta W_b + \Delta W_s + \Delta W_r \quad (9)$$

and using the above equations, the difference equation

$$B(j+1) = B(j) + \Delta B \quad (10)$$

is obtained, where j denotes year and ΔB is the annual change in B. ΔB is a function of only B, C and ΔC. C and ΔC are obtained from GROW.

FITTING THE MODEL

The model was fitted using individual tree diameter growth data. The loss function used is:

$$\sum_{A} \sum_{i=1}^{N(j)} (Dm_{i(j)} - D_{i(j)})^2 \quad (11)$$

where $Dm_{i(j)}$ is the measured diameter (at breast height) of tree i in year j, $D_{i(j)}$ is the corresponding output of the model, N(j) is the number of trees measured in year j and A is the set of years when comparisons are

made. The first measurement was used as the initial condition for model (10).

This is a problem of nonlinear regression analysis. It should be noted that the actual output of the model is a set of growth curves which are compared to a measured set of growth curves. Parameter estimation problems are typically defined this way in the context of dynamical systems in system identification models (cf. Bard 1974, pp. 218-243). In principle, all the parameters in the model can be estimated from measurements of diameter in one fitting. This naturally sets strong requirements on the range and quality of data. The framework for parameter estimation defined here is somewhat different than that generally used in fitting forest stand growth models. Quite often models are fitted using the growth increment as a dependent variable in a regression model. The complexity of the present model is evident from the computational requirements of fitting; fitting (10) to one data set requires about three hours of central processing unit time on a VAX 11/750 equipped with a floating point accelerator.

In the present model some parameters may be assigned values on the basis of their biological definitions, whereas in most forest stand growth models there are no prior expectations about values of the parameters. If parameter values obtained by fitting differ much from prior expectations it can be concluded that the model does not provide a good description, even though residual error might be reasonably small. If data exist from a range of stand conditions, parameter stability may also be studied. Parameter estimates obtained by fitting that vary consistently with stand conditions may indicate a nonsatisfactory, under-parameterized model.

The purpose of fitting this model is exploratory: to find out how models of this type fit using standard statistical fitting procedures and to learn what parts of the model are not adequate. To this end, estimation by minimizing the loss function (11) with a derivative free method was judged satisfactory.

DATA

The data consist of 6 measurements of diameter (at breast height) of all red pine trees on four untreated plots (0.1 ha) on a plantation in northern Wisconsin. Measurements start at age 32 years (from seed) in 1943. Site index is 19.5 m (at age 50 years). The development of some stand characteristics is shown in Table 1.

RESULTS AND DISCUSSION

The total number of parameters in the model, including those in components developed by others (C, stem volume, tree height and branch dry weight), is 26. Of the 10 parameters unique to this model only 6 are simultaneously identifiable (some parameters appear only as a product or almost as a product). That is, the model is over-parameterized <u>for fitting</u> although all parameters are significant in the derivation of the model. Parameter a, associated with site index, is unidentifiable since the data used involved only one site.

TABLE 1. Growth of plots 1 through 4 used in model fitting and validation.

Year	Plot 1 Basal area (m^2/ha)	Plot 1 Trees/ha	Plot 2 Basal area (m^2/ha)	Plot 2 Trees/ha
1943	41	1927	39	1937
1948	46	1858	43	1898
1954	50	1829	46	1809
1961	54	1700	51	1740
1969	58	1572	54	1670
1976	63	1552	58	1611

Year	Plot 3 Basal area (m^2/ha)	Plot 3 Trees/ha	Plot 4 Basal area (m^2/ha)	Plot 4 Trees/ha
1943	40	2372	38	2590
1948	43	2333	43	2540
1954	46	2254	48	2431
1961	51	2184	53	2323
1969	53	1957	58	2224
1976	56	1898	62	2135

Line one of Table 2 shows the results of estimating the five identifiable parameters with data from plot 1. Values for parameters a, m, u and w were not estimated; they were assigned the values given in Table 3. Comparison with typical parameter values obtained from the literature shows that the value of b is much too small. The value of r is also too small.

Because it is well known that b should be slightly greater than 1, the estimated value indicates that problems may exist with the model. Upon closer inspection it was found that some parameter combinations yield an almost massless stem having a reasonable diameter. This shows that the mass variables required to derive the model using the mass balance equation are not necessary for fitting diameter growth using the final model. The low value of r could be caused by an incorrect model component or it may be that the present data are not suitable for estimating r (cf. discussion below). Further study with a more complete data set is required.

To prevent unreasonable results, b was fixed at the value 1.1 and the estimation was repeated (line 2, Table 2). The fit was nearly as good as in the previous case, the value of loss function was only 1 percent larger. The value of r was not fixed because the low value did not produce unreasonable results. Fitting was also repeated using the absolute value of errors instead of squared errors; parameter values changed only slightly. Plots 2, 3 and 4 data changed the parameter values to some extent. Most affected was the maintenance respiration parameter r, which was about double in the denser plots 3 and 4. For these somewhat limited results it seems that the fitting is not very sensitive to loss function specification or to data.

TABLE 2. Estimated parameter values for model (10) using two loss functions and the data described in Table 1.

Plot	Loss Function	Root Mean Squared Error (cm)[a]	p_0	r	y	q	b
1	(11)	1.24	0.0011	0.0029	0.721	0.396	3.41×10^{-5}
1	(11)	1.24	0.0058	0.0033	0.723	0.397	not fitted
1	absolute value	--	0.0048	0.0034	0.765	0.469	not fitted
2	(11)	1.14	0.0057	0.0038	0.617	0.434	not fitted
3	(11)	1.02	0.0050	0.0079	0.623	0.601	not fitted
4	(11)	1.02	0.0074	0.0089	0.577	0.369	not fitted
values from the literature			0.005[b]	0.11[c]	0.75[b]	0.3[d]	1.1[e]

[a] (residual sum-of-squares (see (11))/number of predicted values)$^{1/2}$

[b]-[e] These values were estimated on the basis of: [b] Jarvis and Leverenz (1983), [c] Linder and Troeng (1980), [d] Waring and Schlesinger (1985), and [e] Assuming an inside bark-outside bark ratio of .94, $b = 1/.94^2 \doteq 1.1$.

TABLE 3. Parameters of the photosynthetic model.

Parameter	Units	Value	Equation
p_0	(kg dw)MJ^{-1}	fitted	(1)
k	--	.2	(2)
m	--	.9	(3)
y	--	fitted	(3)
r	--	fitted	(3)
q	$m^2\ cm^{-2}$	fitted	(4)
w	$m^2\ kg^{-1}$	6	(4)
c_1	kg $cm^{-2.4}$	.025	(6)
c_2	--	2.4	(6)
b	--	fitted	(7)
u	kg dm^{-3}	.4	(7)
a	kg cm^{-2}	.09	(8)

Initial attempts were also made to estimate model (10) parameters using plot level data. Loss function (11) was respecified in terms of basal area per hectare. Unsatisfactory results were obtained. Only two of the parameters were estimated well, though the resulting root mean squared error was comparable to that obtained using standard empirical models. A richer set of data (more varied site and stand conditions) may improve the results though additional research will be necessary.

A simple empirical model for diameter growth of an individual tree

$$dD/dt = (p_1 + p_2 CD^{p_3})(1 - \exp(-p_4 D/Dq)), \qquad (12)$$

where p_i's are parameters, Dq is quadratic mean diameter of the plot and C is crown ratio obtained using subroutine of GROW, was fitted to data of plot 1 for purposes of comparison. It fit the data only slightly worse than

model (10) (Table 4). For comparison, the original GROW model was also run using nominal parameter values (Brand 1981) and loss function (11) was evaluated (Table 4). All models were run for plot 2 to compare fit with independent data. In all cases the regionally derived GROW was clearly less accurate than the two other models (as could be expected). The simple model was a little better than model (10) for plot 2. Both models give a clearly poorer result than when plot 2 was used to fit model (10). The result indicates that model (10) may be less robust than the simple model, probably due to the photosynthetic submodel. Similar results were obtained for plots 3 and 4.

TABLE 4. Comparison of models based on square root of average squared error (cm). Models (10) and (12) were fit to plot 1 only.

Model	Plot 1	Plot 2	Plot 3	Plot 4
(10)	1.24	1.20	1.28	1.29
(12)	1.25	1.18	1.10	1.05
GROW	1.93	2.27	--	--

The fitting of the present model shows a number of things: first, a physiologically-based growth model is not necessarily suitable for statistical fitting purposes without modifications. The model may be computationally over-parameterized although all parameters may seem physiologically reasonable. Over-parameterization does not hamper making simulation runs. However, the simulation model may have components which are not required for generating the output used for fitting. One could speak about "over-variablization." This is exemplified in the parameter b: stem dry weight is necessary in deriving growth using mass balance but according to the model, diameter growth can occur even though stems do not (practically) have any mass. This shows that models considered for fitting need to be more carefully designed than simulation models. This problem might be overcome by using more than just one measured variable in the fitting process. For example, diameter, leaf weight, branch weight, and root weight might simultaneously be used as responses with the loss function involving some weighed combination of responses. If the biomasses of tree components had been fitted at the same time as diameter, the problem of a massless stem would not have occurred. However, requiring multiple measured variables limits the number of data sets available for fitting. Second, the data utilized in this study covers the period when increase in tree diameters is quite linear. It may be that some parameters (like r perhaps) do not have a significant effect on model behavior during the linear phase of growth. As evidence for this possibility, when the data set was artificially augmented to induce curvilinearity, convergence to a minimum was more rapid. The model is probably best fit or tested when the data cover all phases of growth.

The results of the study are promising. With a fairly simplified model and only dimensional data on trees and stands, physiological parameters including photosynthetic rate and growth and maintenance respiration were directly estimated. The estimation process also indicated parts of the model which should be subjected to closer investigation. The advantages of the reported modeling approach is that it enables us to quantify basic processes and test hypotheses concerning model specification.

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A GROWTH MODEL OF A SELF-THINNING STAND BASED ON CARBON BALANCE AND THE PIPE-MODEL THEORY

Harry T. Valentine[1]

ABSTRACT. The pipe-model theory provides a structural framework for the derivation of a carbon-balance model that describes the growth of average stem length, total basal area, and total volume of an even-aged, self-thinning, mono-species stand. Variations of the volume-growth function are described for two situations: 1) where the rates of substrate production and feeder-root turnover can be assumed constant over time, and 2) where these rates are expected to change over time such as in environments with air pollution/acid rain. The function describing the growth of stand volume for the first situation has been studied previously and shows good agreement with yield tables.

INTRODUCTION

It has been hypothesized that air pollution/acid rain is causing or contributing to certain forest declines in Europe, Japan, and parts of North and South America and Southeast Asia. Bossel (1986) noted that such hypotheses fit into two categories: 1) those concerning direct damage to foliage by pollutants with consequent deceleration of the rate of assimilate production, and 2) those concerning damage to feeder roots or mycorrhizae with consequent acceleration of the rate of feeder-root turnover. This paper contains a synoptic description of a carbon-balance model of the growth of an even-aged, self-thinning, mono-species stand in which the rate of assimilate production and the specific rate of feeder-root turnover are explicitly isolated. A detailed description of the derivation of the model is given elsewhere (Valentine, 1987).

The structural framework of the model is based on the pipe-model theory of Shinozaki *et al*. (1964*a*,*b*). As shown in Figure 1, the woody components of a stand--branches, boles, transport roots--are represented by assemblages of active and disused pipes. Active pipes extend from leaves to feeder roots providing support and vascular connections. Disused pipes are vestiges of old active pipes that no longer connect foliage to feeder roots. An active pipe becomes disused when its foliage and feeder roots die or are not renewed. Distal portions of disused pipes are lost from a specific tree whenever one of its dead branches is shed. However, the basal portions of those pipes remain within the bole of the tree and a part of the volume of the stand until that tree dies.

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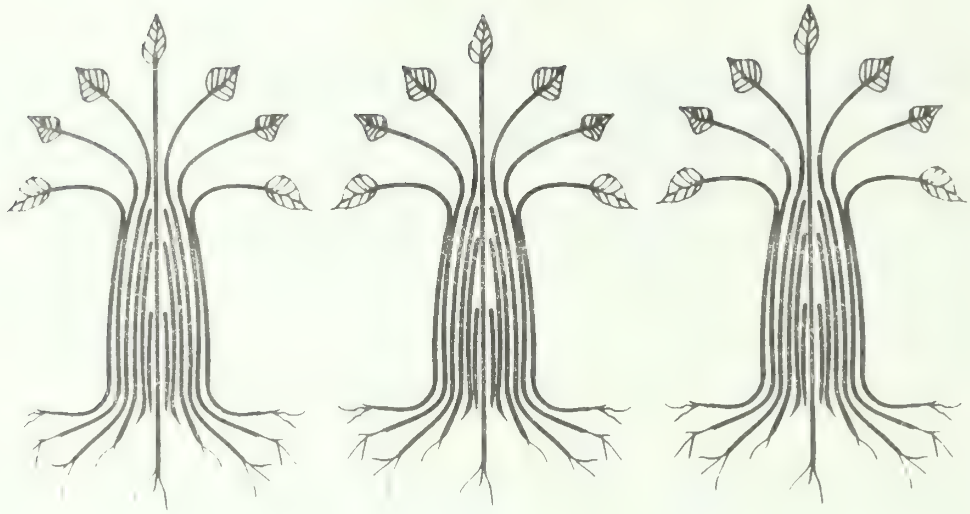

Figure 1. Active pipes connect leaves to feeder roots in the pipe model. Disused pipes, vestiges of once-active pipes, no longer connect leaves to feeder roots. The active and disused pipes, in aggregate, represent all of the woody components of the stand: branches, boles, and transport roots.

According to the pipe-model theory (Shinozaki et al., 1964a), a constant ratio is maintained between the total foliar dry matter of a stand and the total cross-sectional area of active pipes (active-pipe area). An analogous relation is assumed to exist between active-pipe area and feeder-root dry matter. The foliar dry matter of a closed, even-aged, self-thinning stand is maximal (or nearly so) and more or less constant (e.g., Kira and Shidei, 1967; Forrest and Ovington, 1970; Marks, 1974; Mohler et al., 1978) and, therefore, the active-pipe area of the stand also is maximal and constant. Increases in the active-pipe areas of the more rapidly growing trees are compensated by reductions in the active-pipe areas of the slower growing trees. A tree dies when its active-pipe area decreases to zero.

The active-pipe area of an individual tree is approximated by the cross-sectional area of the bole at the base of the crown (Shinozaki et al., 1964b). In some tree species, particularly conifers, active-pipe area may be assumed synonymous to the basal area of conducting xylem (e.g., Waring et al., 1982).

MODEL FRAMEWORK

Variables

A = total active-pipe area of a stand (m^2)

X = total disused-pipe area of a stand (m^2)

L = average length of an active pipe (m)

B = total basal area of the stand (m^2)

V = total woody volume of the stand (m^3)

Growth Rate of Basal Area

The growth rate (per year) of the basal area of a stand equals the sum of the net growth rates of active-pipe and disused-pipe areas:

$$dB/dt = dA/dt + dX/dt \qquad (1)$$

The net growth rate of active-pipe area, dA/dt, is split into a positive fraction (dA^+/dt) and a negative fraction ($-dA^-/dt$), i.e., $dA/dt = dA^+/dt - dA^-/dt$. The positive fraction is the rate of production of new active-pipe area by the living trees in the stand, and in the absence of tree mortality, this rate equals the growth rate of the total basal area of the stand. The negative fraction, $-dA^-/dt$, is the rate of conversion of active-pipe area to disused pipe area. This conversion neither adds nor subtracts from the basal area of the stand. Similarly, the net growth rate of disused-pipe area, dX/dt, is split into a positive fraction (dX^+/dt) and a negative fraction ($-dX^-/dt$), i.e., $dX/dt = dX^+/dt - dX^-/dt$. The positive fraction equals dA^-/dt. The negative fraction is the rate at which disused-pipe area is lost from the stand to mortality. Because $-dA^-/dt + dX^+/dt = 0$, the growth rate of stand basal area can be rewritten as:

$$dB/dt = dA^+/dt - dX^-/dt \qquad (2)$$

In the seminal paper (Valentine, 1987), I used Reineke's (1933) precursor of the self-thinning rule to derive a model of the rate at which disused-pipe area is lost from the stand to mortality; namely,

$$dX^-/dt = \phi dA^+/dt \qquad (3)$$

The parameter ϕ is assumed constant. Thus, in a self-thinning stand:

$$dB/dt = (1-\phi) dA^+/dt \qquad (4)$$

Growth Rate of Active-pipe Length

The growth rate of average, active-pipe length, dL/dt, equals the sum of two fractions: a metabolic fraction (dL_M/dt) and a numerical or non-metabolic fraction (dL_N/dt), i.e.,

$$dL/dt = dL_M/dt + dL_N/dt \qquad (5)$$

The metabolic fraction, dL_M/dt, is the rate at which average, active-pipe length increases due to the apical growth of shoots and

roots. The suppression and disuse of shorter than average pipes increases average, active-pipe length without metabolic expediture. The non-metabolic fraction, dL_N/dt, is the rate at which average, active-pipe length increases due to the disuse of pipes that are, on average, shorter than L. In the seminal paper, I derived the following model of dL_N/dt for stands where $dA/dt = 0$ and $A = A_{max}$ (i.e., self-thinning stands):

$$dL_N/dt = [(1-\theta)L/A_{max}]dA^+/dt \qquad (6)$$

where θL is the average length of a deactivating pipe. The parameter θ is assumed constant.

Growth Rate of Total Volume

The growth rate of the woody volume of a stand, dV/dt, equals the rate of production of new active-pipe volume,

$$LdA^+/dt+AdL_M/dt,$$

minus the rate that volume is lost to mortality and the shedding of branches. Let v_1LdA^-/dt denote the rate that volume is lost to the shedding of branches in connection with the disuse of pipes and let $v_2L(dX^-/dt)$ denote the rate that disused-pipe volume is lost to mortality (where v_1 and v_2 are assumed constant). Therefore:

$$dV/dt = LdA^+/dt-AdL_M/dt-L(v_1dA^-/dt+v_2dX^-/dt) \qquad (7)$$

As was noted, foliar biomass and active-pipe area are more or less constant in an even-aged, self-thinning stand, so $dA/dt = 0$ and the rate of production of new disused-pipe area, dA^-/dt, equals the rate of production of new active-pipe area dA^+/dt. Thus, restricting consideration to self-thinning stands, and substituting dA^+/dt for dA^-/dt and $\theta dA^+/dt$ for dX^-/dt [from eqn (3)], eqn (7) reduces to:

$$dV/dt = (1-v_1-\theta v_2)LdA^+/dt-AdL_M/dt \qquad (8)$$

CARBON BALANCE

I used a carbon-balance approach (e.g., Thornley, 1976) to derive formulae for the rates dA^+/dt and dL_M/dt by setting the sum of the rates of production plus the sum of the rates of constructive respiration of new foliar, feeder-root, and woody dry matter in a stand equal to the rate of production of dry-matter substrate minus the sum of the rates of maintenance respiration for existing foliar, feeder-root, and woody dry matter (represented by the active pipes). All rates had dimensions of kg[CO_2]/year. The rather lengthy derivation yielded the

following equations (Valentine, 1987):

$$dL_M/dt = (1-\lambda)[aI-b_1-b_2/T_f-bL] \quad (9)$$

$$dA^+/dt = \lambda A[aI-b_1-b_2/T_f-bL]/(z^*+L) \quad (10)$$

where I is a variable ranging from 0 to 1 that scales the rate of substrate production by the stand from nil to maximum, T_f is the average ultimate age of a feeder root (years) which may vary over time, and a, b_1, b_2, b, and z* are parameters that, in principle, are calculable from measurable biological fractions or rates.

STAND-LEVEL MODEL

Insertion of eqns (6), (9), and (10) with $A = A_{max}$ into (5) furnishes the growth rate of average active-pipe length in a self-thinning stand; namely,

$$dL/dt = [aI-b_1-b_2/T_f-bL][(1-\lambda)+\lambda(1-\theta)L/(z^*+L)] \quad (11)$$

The quantity $L/(z^*+L)$ should approach 1 in value for large L, as in a self-thinning stand, so the second expression in square brackets on the right-hand side of eqn (11) can be considered constant, whence

$$dL/dt = (1-\theta\lambda)[aI-b_1-b_2/T_f-bL] \quad (12)$$

If I and T_f remain constant over the span of time from t to $t + \Delta t$, eqn (12) can be integrated to yield the growth function:

$$L(t+\Delta t) = k_1+k_2I(t)+k_3/T_f(t)+k_4L(t) \quad (13)$$

where

$$k_1 = -b_1(1-k_4)/b$$

$$k_2 = a(1-k_4)/b$$

$$k_3 = -b_2(1-k_4)/b$$

$$k_4 = \exp[-b(1-\theta\lambda)\Delta t]$$

Similar arguments give rise to the basal area growth function:

$$B(t+\Delta t) = B(t)+k_5\{\ln[L(t+\Delta t)+z^*]-\ln[L(t)+z^*]\} \quad (14)$$

and the volume growth function:

$$V(t+\Delta t) = V(t)+k_6[L(t+\Delta t)-L(t)] \quad (15)$$

or

$$V(t+\Delta t) = k_7+k_8I(t)+k_9/T_f(t)+k_4V(t) \quad (16)$$

where the k_i's are functions of $\theta, \phi, \lambda, v_1, v_2, a, b_1, b_2, b, z^*$, and a constant of integration [see Valentine (1987) for details].

DISCUSSION

If I and T_f are constant in an invariant environment, then eqn (16), which describes total volume growth of an even-aged self-thinning stand, reduces to a Mitscherlich function, i.e.,

$$V(t+\Delta t) = k_{10}+k_4 V(t) \qquad (17)$$

where $k_{10} = k_7+k_8 I+k_9/T_f$. Previously, Khil'mi (1957) used a model analogous to eqn (17) to describe the aboveground growth of even-aged, self-thinning stands and obtained good agreement between the model and yield tables. Khil'mi showed empirically that the intercept, k_{10}, increases with site quality, whereas the slope, k_4, remains fairly constant among sites of differing quality. The present theoretical model supports the conclusions of Khil'mi inasmuch as k_4 is a constant and k_{10} is a function of I and T_f, which are known to vary among stands on sites of differing quality. Although the model derives from theories about and observations from even-aged, self-thinning, mono-species stands, conclusions about k_4 and k_{10} may apply to some mixed-species stands as well. For example, eqn (17) fits mixed-oak yield curves with a high degree of precision (see Figure 2).

As was noted, the present model applies only to even-aged, self-thinning stands. The assumption of constant foliar dry matter does not apply during the period between the establishment and closure of a stand, nor does it apply during the period between a silvicultural thinning (which, by constrast to self-thinning, creates gaps in the canopy) and closure of the stand. During these periods, foliar dry matter and, therefore, active-pipe area normally are increasing. Consequently, differential equations describing dA/dt and dI/dt are needed to complete the model for these situations.

A reduction in the rate of substrate production by a stand in the model, attributable to air pollution/acid rain or other causes, is achieved by reducing the value of the scaling variable I. An increase in the specific rate of feeder-root turnover (T_f^{-1}) obviously is achieved by decreasing the value of T_f. Unfortunately, estimation of the parameters of eqn (16), the volume-growth model in which T_f and I are explicitly included, is impossible by regression techniques because the requisite time-series data do not exist, as far as I know, for any stands, anywhere. All is not lost, however, because eqn (17) is derived from ecophysiological theory and observations. All of the parameters

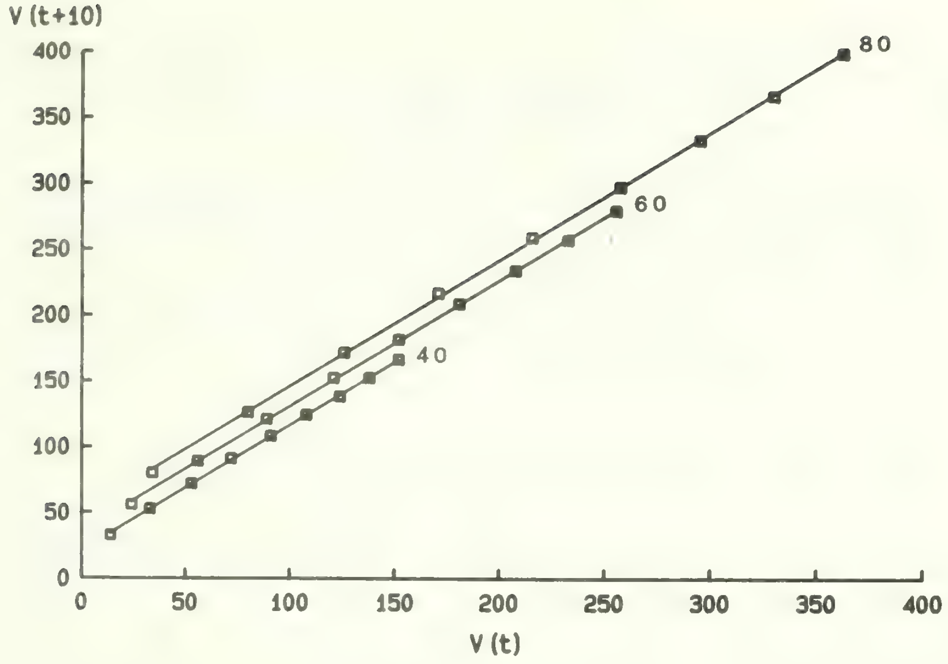

Figure 2. Total aboveground volume (m^3/ha) in year t+10 vs. total aboveground volume (m^3/ha) in year t for mixed-oak (Quercus spp.) stands with site indices of 40, 60, or 80. Data points for stands aged 10 through 90 (years) in years t are from Schnur(1937:table 12). The solid lines are least-squares fits of eqn (17). The common slope, k_4, of the three fitted lines is 0.951. Intercepts, k_{10}, for site indices 40, 60, and 80 are, respectively, 21.1, 35.4, and 50.4 ($r^2 > 0.99$; se = 1.35).

of this and the other equations of the model have physical definitions and can be assigned values based on measurements or theory. Moreover, all of the assumptions of the model are hypotheses that can be tested experimentally.

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FPES: A FRAMEWORK FOR MODELLING THE ARTIFICIAL REGENERATION SYSTEM

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ABSTRACT. An artificial regeneration model, FPES, was developed for conifers in the Great Lakes region. A microcomputer program that incorporates the model framework is described. The use of the program is demonstrated by examining the efficiency of the following three general site preparation treatments for 3-0 red pine seedlings with regard to expected growth, survival and cost: cultivation, furrowing, and scalping.

When efficiency is measured by the cost per surviving tree, the least intensive site preparation treatment, scalping, is judged to be the best alternative. However, when the efficiency measure is modified to also reflect growth, the most intensive site preparation treatment, cultivation, is favored. The two measures of efficiency, (1) cost per surviving tree and (2) cost per 1000 cm of aggregate growth, vary in their sensitivity to changes in cost estimates for the three treatments. Changes in cost of as little as \$5.00 per acre are enough to affect the recommendation based on measure (1); whereas changes of as much as \$60.00 per acre do not affect the choice of alternatives based on measure (2).

The development of FPES represents a "first step" in modelling the artificial regeneration system. Many refinements to the framework are needed to provide users with a practical management tool. The most important of these refinements include: stock quality estimation by physiological means, estimation of planting site quality, and quantification of seedling stress due to competition pressure.

INTRODUCTION

The practice of artificial regeneration has been a part of forestry in the Great Lakes region of North America for many years. Published documentation of plantations and planting experiments began at least as early as the 1920's (e.g., Richardson, 1924; Hansen, 1927; and Kittredge, 1929), and continues today. Much is known about the individual factors affecting seedling survival, growth, and production costs. However, researchers have only recently begun to systematically address the interrelationships of these factors.

Regeneration modelling in the Great Lakes region was initiated by Payandeh and Tucker (1975) in Ontario. The authors used a semi-stochastic approach employing "subjective probability estimates derived from the forest manager's total experience and opinion"

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regarding the potential success of various regeneration alternatives. The resulting model, called REGEN, provided a range of likely outcomes that addressed tradeoffs between various levels of success and the cost of treatments. REGEN was further documented by Payandeh (1975 and 1977) and Payandeh and Field (1978), and recently expanded to include general silvicultural treatments and management options over the life of the stand (Payandeh and Field, 1985).

As an alternative to this subjective approach, research was initiated in Minnesota to incorporate the vast amount of published results concerning regeneration experiments into a suitable model framework. The study progressed through five distinct stages: (1) data collection and summarization from published experiment results; (2) identification of those factors demonstrating consistent influence on tree performance; (3) development of growth and survival functions based on these factors; (4) estimation of costs of various regeneration activities; and (5) the construction of a microcomputer-based simulation program combining the economic information with the growth and survival functions. A detailed description of the model development process and the resulting model functions has been reported by Belli (1986).

PROGRAM DESCRIPTION

The simulation program, called Forest Plantation Establishment Simulator (FPES), is driven by two fundamental models; one to estimate annual height growth of planted trees, and one to estimate percent survival. The growth expression is,

$$G_t = b_1(t^{b_2} - (t-1)^{b_2}) * \left[1 + \frac{1 - e^{(b_4 D_1 + b_5 D_2)^{b_6}}}{b_3} \right] \qquad (1)$$

where,

- G_t = expected tree height growth in year t
- t = years after planting (counted after each growing season), limited to t=1,2,3,4,5
- D_1 = delay in stock lifting past earliest viable date (days)
- D_2 = delay in planting after lifting, through cold storage of stock (days)
- b_i = coefficients

A similar expression is used for the estimation of survival,

$$S_t = 100\, e^{-b_1 t^{b_2}} * \left[1 + \frac{1 - e^{(b_4 D_1 + b_5 D_2)}}{b_3} \right] \quad (2)$$

where,

S_t= expected survival at the end of year t (in percent of total trees planted)

Both equations (1) and (2) incorporate the same critical factors and make use of the same general form; a combination of a potential performance function with a modifier function. Potential tree performance (growth or survival) is estimated by the expressions outside the brackets in (1) and (2), which were fit to data categorized by the following factors: species, stock type, age class, harvest history, and site preparation. The functions within the brackets are used as modifiers to adjust for the detrimental effects of lifting and planting delays (during the spring planting season) on potential tree performance.

The prediction of growth and survival of planted trees constitutes only part of the FPES program. An important aspect of regeneration planning is the economic desirability of management alternatives. Hence, default values of cost estimates for planting stock, planting, and site preparation (based on a survey of forest managers and nurserymen) are included as part of the program (e.g., Table 1 for 3-0 red pine). Users are also prompted to input their own estimates of these costs, if available.

TABLE 1. Estimates of average regeneration costs for 3-0 red pine plantations[a] (from Belli, 1986).

	Cost ($/1000 trees)
Planting Stock	77.70
Hand Planting	106.00[b]
Site Preparation	Cost($/acre)[b]
cultivation (or disk)	60.00
furrow	21.78
scalp	25.92

[a] All values 1986 prices, or inflated to 1986 levels at rate of 4% per year.

[b] Includes labor, equipment, and supervision.

The output of FPES consists of predicted average plantation growth (both annual and cumulative) and survival for years one through five after planting. Two measures of cost effectiveness are then calculated to assess the relative efficiency of different management strategies. The first measure, originally suggested by Stoeckeler

(1963), is simply the cost (in dollars) per planted tree surviving to the end of year five. The second measure incorporates all three plantation attributes; growth, survival, and cost. It is a modification of the term developed by Haig and Curtis (1974). These authors suggested the use of "cost per foot of aggregate height," whereas FPES provides the "cost per 1000 centimeters of aggregate growth." Aggregate growth is defined as the product of the total number of trees alive at the end of a given year and that year's average cumulative plantation growth.

FPES is intended for eventual use as a management tool; however, at this stage it has limitations. Users should be aware of the numerous assumptions that were made in the construction of the growth and survival functions and the estimates of the default values for plantation costs. Management choices were strictly limited to those for which data were available and, therefore, did not cover the entire spectrum of regeneration alternatives. Furthermore, the model has been calibrated for only two species, red pine (Pinus resinosa Ait.) and white spruce (Picea glauca (Moench) Voss). A final caution is that growth and survival models were fit to data concerning experimental, rather than operational, plantations. Therefore, estimates are expected to be positively biased as indicated by the work of Pierpoint et al. (1981).

EXAMPLE OF PROGRAM USE

A typical management scenario was chosen to illustrate the use of FPES. Alternative site preparation treatments were examined for 3-0 red pine seedlings planted on old field sites; default cost estimates were used. The three choices for site preparation method were cultivation, furrow, or scalp. When efficiency was judged merely

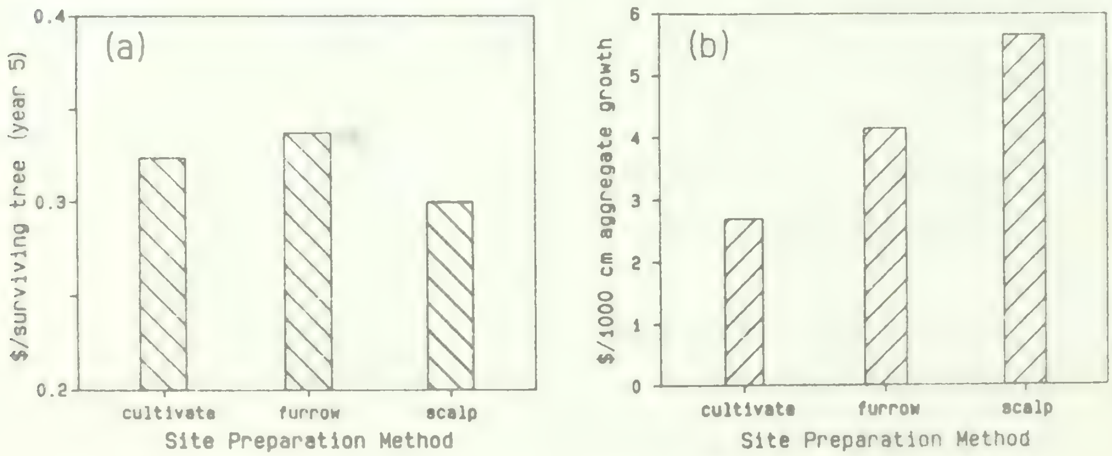

Figure 1. A comparison of three site preparation methods based on (a) cost per surviving tree (efficiency measure #1) and (b) cost per 1000 cm aggregate growth (efficiency measure #2).

by the cost per live tree at age five (efficiency measure 1), scalping appeared to be the best site preparation option, followed by cultivation and furrow (see Figure 1a). Apparently, the low cost of scalping compensated for the survival rate being less than for the trees on the cultivated site.

Alternatively, when efficiency was judged by cost per thousand centimeters of aggregate growth (efficiency measure 2), cultivation was shown to be much more desirable than scalping (see Figure 1b). The cumulative growth levels for cultivation and furrowing were so much higher than those for scalping that the ranking of treatments (from best to worst) using this second measure of efficiency was: cultivate, furrow, scalp.

SENSITIVITY ANALYSIS

Within the framework of the example management scenario the sensitivity of the efficiency measures to changes in site preparation costs was explored. The cost per acre for the different methods had been estimated to range from a minimum of $21.78 to a maximum of $60.00 (see Table 1). For the sensitivity analysis, this entire range of costs was examined in $5.00 increments. Table 2 summarizes the corresponding changes in both measures of efficiency.

The absolute change in terms of efficiency measure 1, from the minimum to the maximum cost per acre, appeared to be about the same for all three site preparation methods; an average of $0.071 per surviving tree at year 5. The change per $5.00 cost increment was approximately $0.009.

When rankings of these site preparation methods were considered, the efficiency of scalping was the least sensitive to changes in cost. Cost changes of up to $15.00 per acre for scalping did not effect the order of the treatment rankings. However, changes in cultivation or furrowing costs as little as $5.00 per acre could reverse their respective ranks. This implied that cost estimates for site preparation need to be accurate to within $5.00/acre for the first measure of efficiency to be meaningful.

When the second measure of efficiency was examined it was clear that cultivation was much less sensitive to fluctuations in cost than either furrow or scalp (see Table 2). For each $5.00 cost increment, cultivation efficiency averaged a change of only $0.065 per 1000 cm of aggregate growth. Furrowing and scalping efficiency, however, changed by $0.123 and $0.164 for the same $5.00 cost increment; approximately twice the rate of change for cultivation.

The predicted rank of site preparation treatments by efficiency measure 2 was cultivation, furrow, and then scalp (Table 2). Unlike the first efficiency measure, the use of measure 2 was shown to be insensitive to cost changes when ranking treatments. For cultivation to be ranked lower than furrow it would have had to cost over $170.00 per acre. To be ranked lower than scalp, it would have had to cost over $280.00 per acre. From a different perspective, if cultivation

TABLE 2. Sensitivity of two measures of efficiency to changes in site preparation costs.

Cost ($/acre)	Efficiency Measure #1[a]			Efficiency Measure #2[b]		
	Cultivate	Furrow	Scalp	Cultivate	Furrow	Scalp
60	0.324	0.413	0.359	2.683	5.083	6.786
55	0.317	0.403	0.350	2.618	4.961	6.622
50	0.309	0.393	0.342	2.553	4.838	6.458
45	0.301	0.383	0.333	2.488	4.715	6.294
40	0.293	0.373	0.324	2.423	4.592	6.130
35	0.285	0.363	0.315	2.359	4.469	5.966
30	0.277	0.353	0.307	2.294	4.347	5.802
25	0.270	0.343	0.298	2.229	4.224	5.639
20	0.262	0.333	0.289	2.164	4.101	5.475

[a] Measure #1: $/surviving tree at year 5.

[b] Measure #2: $/1000 cm aggregate growth (aggregate growth defined as the product of the total number of live trees and total growth at the end of year 5).

costs were to remain at $60.00 per acre, neither furrowing nor scalping would be as efficient even if they were both free. Furthermore, even though furrow and scalp treatments were more sensitive than cultivation to cost changes, neither would change ranks with the other for changes less than $60.00 per acre. Therefore, unless a user was certain that site preparation costs were known to within $5.00 per acre efficiency measure 2 would tend to be more reliable than the first in terms of treatment ranks.

This sensitivity analysis illustrates the need to fully explore the results of comparative management scenarios in terms of the two measures of efficiency before making any decision on management strategy. Particular attention should be paid to those situations in which slight fluctuations in parameters can be shown to heavily influence the relative efficiency ranks of alternative strategies.

RESEARCH DIRECTIONS

The results of the modeling effort should be considered as a "first step" in an ongoing effort to fully characterize the regeneration system. This system can be divided into three main components: (1) the potential of seedlings to perform in the field, (2) the ability of a particular planting site to physically support planted trees, and (3) the interaction between seedlings and the other vegetation present on the site. A substantial amount of research remains to be done in all three areas, and an effort must be made to address the system as a whole.

Research into the estimation of seedling potential, or quality, should focus on physiology, rather than morphology. The operational use of

physiological measures of stock quality has been somewhat neglected in favor of more easily determined morphological measures. Unfortunately, seedling morphology has seldom been shown to be a reliable indicator of performance potential (Sutton, 1979).

The quantification of physical site characteristics as they relate to the potential growth and survival of planted trees is an area that merits attention. A measure, or index, of site potential might include such factors as expected average climatic conditions, topography, soil characteristics, or even an estimate of site index for tree species that had occupied the site in the past.

Finally, studies are needed to objectively describe the competition pressure during a seedling's early years in the field and the corresponding response of young trees to relief of this pressure through various site preparation or release treatments. The key to such investigations is the development of a meaningful competition index sensitive to the reductions in moisture and light available to seedlings caused by weeds (see Strothmann, 1967). A suitable index has been hypothesized for Douglas-fir by Brand (1986). The testing and modification of such an index for species in the Great Lakes region should be a top priority in future regeneration research.

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DEVELOPING VARIANTS FOR THE REGENERATION ESTABLISHMENT MODEL

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ABSTRACT. Conifer establishment following operational harvest and site preparation treatments can be predicted for the grand fir-cedar-hemlock ecosystem in northern Idaho. The Regeneration Establishment Model predicts the probability of stocking, trees per acre, species composition, and tree heights from 3 to 20 years following harvest and is linked to the Prognosis Model, an individual-tree, distant-independent growth and yield model. Variants of the Prognosis Model have been adapted to several locations throughout the Western United States. This paper describes how existing inventory data can be used to modify the Regeneration Establishment Model to predict regeneration where a Prognosis Model variant exists. An example shows the process for a southeast Alaska Regeneration Model.

INTRODUCTION

Stage (1973) envisioned three submodels for the Prognosis Model: development of larger trees, development of regeneration, and ingrowth of regeneration. The first two submodels are described by Stage (1973), Wykoff et al. (1982), and Wykoff (1986) for northern Idaho, while the ingrowth of regeneration is described by Ferguson et al. (1986) and Ferguson and Crookston (1984). The Prognosis Model has been calibrated for other locations in the Western United States, but these versions of the Prognosis Model (called variants) presently lack the capability to predict regeneration following a disturbance.

A considerable amount of work needs to be done if each Prognosis Model variant is to have a reliable regeneration submodel. We had an opportunity to develop a regeneration model variant for southeast Alaska. The process of developing this variant has application to other areas in the Western United States.

THE PROGNOSIS MODEL

The Prognosis Model is an individual-tree, distant-independent, growth and yield model originally developed for forests of northern Idaho. The model predicts growth and mortality for an inventory of sample trees in a stand. Sample trees are represented in the model by a tree record.

A tree record represents a trees per acre value obtained from an inventory. Yield tables are tabulated by summing the value of all trees in the inventory. Growth is simulated by predicting successive increments of growth, while mortality is a predicted reduction in the

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trees per acre values. Silvicultural prescriptions are easily invoked through the use of keywords that define the type of treatment, its timing, and specifications such as the size of trees to be cut.

Although the spatial relationship of trees in the stand is not used as an independent variable to predict growth and mortality, the inventory plot identification is stored as part of each tree record. This information can be accessed by Prognosis Model extensions.

THE REGENERATION ESTABLISHMENT MODEL

The Regeneration Establishment Model predicts conifer establishment following operational harvest and site preparation treatments. Empirically derived equations determine the probability of stocking for 1/300-acre plots, trees per acre, species composition, and beginning tree heights at times from 3 to 20 years since disturbance. The probability of stocking for 1/300-acre plots is an important part of the model because it scales the results of predictions on stocked plots. The model predicts stocked plot attributes (number of trees, species, and heights). These attributes are multiplied by the probability of stocking and scaled to per acre values. Model users can evaluate the probability of stocking (distribution), trees per acre (density), and species composition to judge expected effectiveness of regeneration prescriptions.

The Regeneration Model uses plot-specific attributes as independent variables. Slope, aspect, type of site preparation, habitat type, overstory density, and overstory species composition are all important. Post-harvest plot overstory density and species composition are known because the Prognosis Model stores plot identification as part of each tree record. Inventory plots are processed separately, so variations in site, treatment, and stand conditions are reflected in the prediction.

The Regeneration Model is presently coded for northern Idaho and is being expanded to forests in central Idaho and western Montana. Where a Prognosis Model variant exists without a calibrated regeneration model, new trees can be added to the tree list using a planting option.

A statistically sound study design for data collection is important for regeneration models because unbiased estimates of rates of establishment and species composition are vital for forest planning. Data collected for the northern Idaho Regeneration Model began with a stratified random sample of operationally-harvested stands. Stands were categorized by habitat type, site preparation, regeneration method, and geographic location. Within each of these combinations, four to five stands were randomly chosen for sampling. Transect lines were drawn on aerial photos to cover variations in overstory density, topography, site disturbance, and so on. This effort was to keep plots within stands as independent as possible. An additional means of keeping plots independent within stands was to record individual plot attributes such as slope, aspect, habitat type, site preparation, and overstory (if present). An average of 25 plots per stand were sampled so that more stands could be sampled instead of more plots per stand.

The Regeneration Model predicts the net result of ingrowth during the first 20 years since disturbance. This follows from sampling stands having a range of treatment dates. Regression equations then predict stocking as a function of time since disturbance. Two tallies of regeneration are predicted, and defaults are 10 and 20 years since harvest. The first tally predicts regeneration since harvest while the second tally predicts additional regeneration since the first tally up to the time of the second tally. Because equations predict the net result over time, background mortality rates of the Prognosis Model are not invoked on regeneration during the 20-year regeneration period.

SOUTHEAST ALASKA REGENERATION MODEL

The process of developing a Regeneration Establishment Model for the southeast Alaska Prognosis Model variant began with reviewing the regeneration systems, ecology, species' silvical characteristics, and sources of data in southeast Alaska. Information came from silviculturists in the Juneau office of the Forest Service and Harris and Farr (1974). Important points were as follows:

- Clearcutting is the most common regeneration method. Partial cuttings are uncommon because of the general overmature nature of these forests and the frequent occurrence of wind storms. Therefore, data were insufficient to include the effects of residual basal area at this time.

- If sites are burned, productivity increases during the regeneration period. However, conditions necessary for prescribed burning occur infrequently and only a small proportion of stands are burned.

- Sitka spruce (*Picea sitchensis*) is the species most often planted. In fiscal year 1986, only 752 acres were planted in the Alaska Region compared with 9,968 acres that had natural regeneration with no site preparation (USDA Forest Service 1987).

- Seedlings become established in abundant numbers, and few plots are nonstocked unless they are nonstockable because of rock, water, etc.

- Scraping away the duff layer during harvest or site preparation makes regeneration subject to frost heaving.

- Sitka spruce and western hemlock (*Tsuga heterophylla*) are the two most abundant species. Incidental species are western redcedar (*Thuja plicata*) and Alaska yellow cedar (*Chamaecyparis nootkatensis*). Alaska yellow cedar grows on the poorest sites.

- Advance regeneration (seedlings that became established prior to the harvest) are mostly western hemlock. Subsequent regeneration is dominated by Sitka spruce up to about stand age 70 when hemlock again becomes established in the understory.

- Elevation has an important effect on regeneration success. Optimum elevation is near sea level with timberline at about 1,000 feet.

- Slope and aspect are important with south aspects being better sites.

- Available inventory data from almost 1,000 sample points used 1/500-acre plots to sample regeneration (USDA Forest Service 1984).

Our objectives were to develop equations predicting regeneration for southeast Alaska forests and recode the model. Another consideration was to keep the model compatible with the user's guide (Ferguson and Crookston 1984).

The area included in the model was the Tongass National Forest. Data were obtained from inventory records collected by USDA Forest Service personnel during routine stand examinations of harvested areas.

Site index is the driving variable in the southeast Alaska variant of the Prognosis Model. Equations developed by Farr (1984) predict top height of the tallest 40 trees per acre in even-aged stands. For the Regeneration Model, these equations are used to predict top height for regeneration-size trees as a function of time since disturbance.

PROBABILITY OF STOCKING

Seedling establishment is a near certainty by stand age 2. Therefore, it was not necessary to develop equations predicting the probability of stocking, and this value was set to 1.0.

TREES PER STOCKED PLOT

A Weibull distribution function (Bailey and Dell 1973) of trees per acre was fit using data from the 1,000 plots. The equation is

$$TPA = B((-(\ln(1-X)))^{1/C}) \tag{1}$$

where TPA = predicted hundreds of trees per acre
$B = 20.48 + 1.22 \cdot RTOP40 - 0.026 \cdot RTOP40^2$
$C = 1.32 + 0.033 \cdot RTOP40 - 0.00088 \cdot RTOP40^2$
X = a uniformly distributed pseudo-random number in the interval [0,1]
$RTOP40$ = top height of the 40 tallest regeneration-size trees

The predicted trees per acre is scaled to a 1/500-acre plot size and rounded to the nearest integer. The random number is used to mimic the plot-to-plot variation found in these stands. Thus, all plots do not receive the same number of trees.

SPECIES COMPOSITION

The probabilities of species occurring on 1/500-acre plots are determined by regression equations for western hemlock and sitka spruce. Data were insufficient to develop equations for western redcedar and Alaska yellow cedar so these probabilities were set at their means; 0.05 and 0.01 respectively. Other species--white spruce (<u>Picea glauca</u>), Pacific silver fir (<u>Abies amabilis</u>), mountain hemlock (<u>Tsuga mertensiana</u>), lodgepole pine (<u>Pinus contorta</u>), and subalpine fir (<u>Abies lasiocarpa</u>)--have zero probability of occurrence but can be added to the inventory using a planting option.

TREE HEIGHTS AND DIAMETERS

Weibull regression equations were developed by species and advance or subsequent germination status. These equations represent the distribution of heights for the 40 tallest regeneration-size trees. A random number is drawn for each tree to vary heights as would be encountered in nature. As an example, height of advance western hemlock is

$$HT = B((-(\ln(1-X)))^{1/C}) \quad (2)$$

where HT = predicted height in feet
B = 2.4911 +0.2732•RTOP40
C = 1.6
X = a uniformly distributed pseudo-random number in the interval [0,1]
RTOP40 = top height of the 40 tallest regeneration-size trees

Figure 1 shows actual distributions of tree heights from the data available to develop equations. Early in the life of the new stand, the distribution is characterized by a reverse-J shape. Over time, mean height increases and the distribution flattens and becomes more symmetrical. Finally, the distribution flattens considerably with fewer and fewer trees represented in the smaller height classes.

Trees less than 4.5 feet tall are assigned a nominal diameter at breast height (dbh). When trees grow past 4.5 feet, dbh is predicted from height with adjustments for stand density and relative size (Wykoff 1986).

STOCKING VERSUS TREES PER ACRE

A new subroutine was written to adjust the trees per acre represented by a tree record. The reason is total number of trees per acre increases until about 15 years after harvest and then begins to decline. Up until the time of maximum seedling density, percentage of stocked plots increases as the stand becomes stocked. After density peaks, trees per acre decline due to competition, but there is no decrease in percent stocking. Said another way, competition sets in and the best trees continue to grow while poor trees are crowded out. Top height of the dominant trees is a good predictor of the number of trees per acre.

The Regeneration Model predicts the net increment of stocking for up to 20 years after harvest. If the probability of stocking increases between the first and second tally, new tree records are generated. If there is no increase in the probability of stocking, the trees per acre values for the first tally are reduced to expected trees per acre values at the time of the second tally. After the second tally of regeneration is predicted, background Prognosis Model mortality rates are applied.

DISCUSSION

Procedures outlined in this paper resulted in a Regeneration Establishment Model variant for southeast Alaska forests. The structure of the model remains the same and only one new subroutine was needed. Data used to develop new equations were collected from operationally harvested

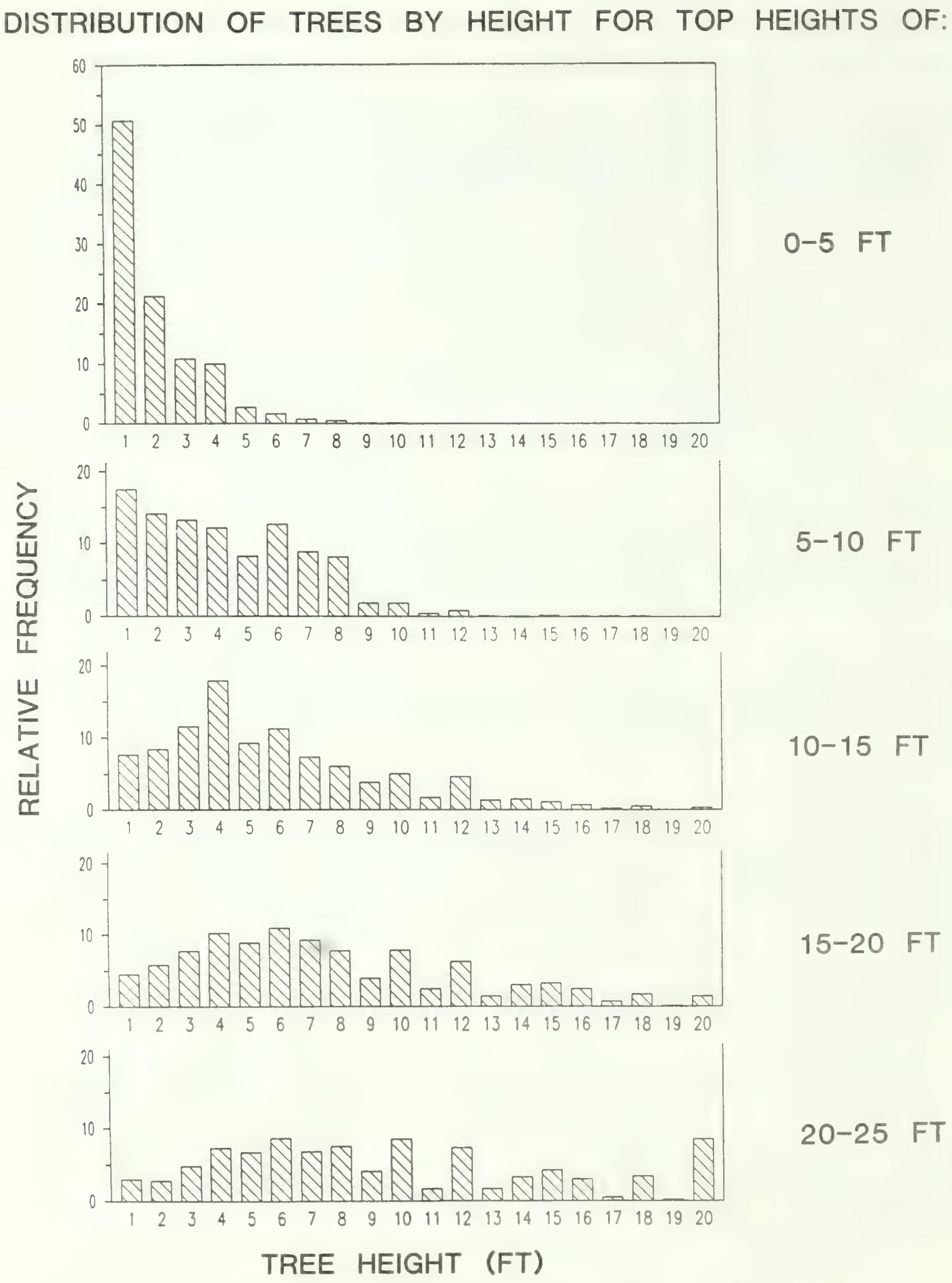

Figure 1. Distribution of tree heights within stands by top height.

stands. Time needed to develop new equations and recode the model was about 10 weeks. Model validation and testing are under way.

The probability of stocking is an important part of the northern Idaho version of the Regeneration Model. However, in southeast Alaska, stocking on 1/500-acre plots is almost a certainty, and we set this value at 1.0 rather than develop new equations.

Other variants may need a good deal of work to develop probability of stocking equations because unbiased estimates are so important. We suggest a study that selects sites in an unbiased fashion from a list of all possible candidate stands. A good source of data is regeneration studies that used random stand selection procedures. These data may be available from authors such as Seidel (1979), Stein (1981), etc. Some authors have developed equations that could be encoded in Regeneration Model variants.

The next-best alternative is to use inventoried stands that are sampled during routine examinations following regeneration cuttings. Avoid inventories from subjectively chosen stands because the selection process may introduce unwanted biases.

Regeneration model variants need to be periodically updated to account for changes in technology, to incorporate new silvicultural techniques, and to account for long-term weather/disease/insect patterns. Data to update the model are most easily obtained from ongoing inventories routinely performed following harvest and site preparation treatments.

Cooperation between managers and researchers is desirable. Data collection procedures must be well documented to collect useful data that are consistent among field crews and from one year to the next. Perhaps randomly selected stands could be designated for sampling by experienced field crews to build up a data base of stands. Some examples of coordination between managers and researchers are:

- Use the same size microsite plot, or at least a few common sizes.

- Explicitly define variables such as when a tree is established, what is a cull tree, etc.

- Record plot attributes to increase sensitivity of model predictions.

- Use a common plot center for fixed and variable radius plots.

- Independent variables should be those in common use in the region. This increases the utility of the model.

- Record at least one tree of each species established on the plot to indicate the distribution of that species throughout the stand.

Regeneration inventories can serve many purposes. National Forests in the Western United States are beginning to store these inventories and retrieve them as needed. Data are easily accessed on computer files.

Examples of uses are certification of stocking as required by the National Forest Management Act of 1976, growth rates, plantation success, brushfield problems, animal damage, thinning needs, etc. The opportunities for land managers and researchers to work together look good, and we can begin now to collect the data for future analyses.

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QUANTIFYING REGENERATION POTENTIALS OF QUERCUS FORESTS IN THE MISSOURI OZARKS

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ABSTRACT. The regeneration potential of oak (*Quercus* spp.) forests under even-aged management in the Missouri Ozarks can be predicted from (1) the number, size, and distribution of the oak advance reproduction, and (2) the composition and structure of the oak overstory, which can be used to estimate stump sprouting. When linked to a tree area (stocking) equation, estimates of developmental probabilities for both types of regeneration provide a basis for predicting, before final overstory removal, the adequacy of stocking by codominant and dominant oaks in the new stand at age 20.

INTRODUCTION

In even-aged stands managed for oak sawtimber, the regeneration period begins before final overstory removal because successful regeneration largely depends on the presence of oak advance reproduction. However, when oak stands reach maturity, oak reproduction often is inadequate for successful regeneration. Earlier studies showed that successful oak regeneration depends on the number, size, and distribution of these advance reproduction stems (Sander 1972, Sander and Clark 1971). Using these attributes of oak advance reproduction, it is possible to estimate the contribution of this reproduction to the stocking of the new stand before removing the overstory.

Oak reproduction also may originate from the stumps of parent trees after overstory removal. The likelihood that a stump will produce a sprout that develops into a codominant or dominant tree can be predicted from characteristics of the parent tree and site quality (Johnson 1977). Thus, the development of the two primary components of the new stand, advance reproduction and stump sprouts, can be predicted from tree and site characteristics that are measurable before final overstory removal. This paper describes a two-step method for determining the adequacy of the total oak regeneration potential of stands in the Missouri Ozarks by evaluating (1) the oak advance reproduction potential and (2) the stump sprouting potential of the parent stand.

PREDICTING THE CONTRIBUTION OF OAK ADVANCE REPRODUCTION TO FUTURE STOCKING

In the Missouri Ozarks, the numbers of oak advance reproduction stems (trees <4.1 cm dbh) range from less than 800 to more than 5,000 per hectare. However, amount of oak advance reproduction alone is not a good indicator of whether or not oaks will be a major component of a new

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stand after final harvest cutting. This is because much of the reproduction may be too small to successfully compete with associated woody vegetation. Thus, tree size as well as tree numbers should be considered in evaluating the growth potential of oak advance reproduction.

Variation in the size of oak advance reproduction stems is related to recurrent stem dieback, which produces seedling-sprouts--the predominant growth form in Ozark oak forests. Consequently, the root systems of large seedling-sprouts are much older than the stems and after overstory removal produce much greater height growth than recently established seedlings and small seedling-sprouts. Both stem height and diameter indicate the potential of root systems to support rapid height growth after overstory removal (McQuilkin 1975, Sander 1972).

ESTABLISHING A FUTURE STOCKING GOAL

Although the regenerated stand does not need to be fully stocked immediately, there needs to be enough dominant and codominant oaks to provide adequate stocking sometime in the future. We defined adequate stocking as stands at least 30-percent stocked with dominant and codominant oaks when the mean stand diameter (dbh) is 7.6 cm [C level as defined by Gingrich (1967)]. Trees of other species and smaller oaks will further increase total stand stocking.

Unmanaged oak stands on average sites (black oak site index 18.3-22.9 m) in the Missouri Ozarks reach a mean stand dbh of 7.6 cm at age 20 to 25, and the dominant and codominant trees average 11.4 cm dbh. According to the stocking equation for defining minimum tree area (Rogers 1980), one 11.4-cm tree contributes 0.055-percent stocking and requires 5.5 m^2 of growing space. To attain the 30-percent stocking goal thus requires 30/0.055 or 545 trees per hectare averaging 11.4-cm dbh when the mean stand dbh is 7.6 cm.

The appropriate unit for sampling oak advance reproduction stems also should be related to the minimum growing space requirements of the average dbh of dominant and codominant trees when the mean stand diameter is 7.6 cm. Because an 11.4-cm tree requires 5.5 m^2 or 1/1,818 ha of growing space, the opportunity exists for each of the 1,818 sample spaces per hectare to contain one 11.4-cm tree. At or beyond a mean stand dbh of 7.6 cm, more than one dominant or codominant tree would not be expected to persist within this sample space. Thus, the appropriate plot size is 5.5 m^2 (1.323-m radius).

ESTIMATING "SUCCESS" PROBABILITIES

To determine the relation between oak advance reproduction size and its growth after overstory removal, we measured 394 reproduction stems under six mature stands in the Missouri Ozarks immediately before and 5 years after clearcutting. Eighty-five percent of these stems were black oak (*Quercus velutina* Lam.) and white oak (*Q. alba* L.) and the remainder were scarlet oak (*Q. coccinea* Muenchh.) and northern red oak (*Q. rubra* L.). Site index for black oak in these stands ranged from 15.2 to 21.3 m (50 to 70 ft) at an index age of 50 years (McQuilkin 1974).

We used the heights of oak stump sprouts as the standard for defining oak reproduction success because of the sprouts' rapid growth and predominance in the upper crown strata of these 5-year-old stands. We defined a "successful" oak as one that attained at least 80 percent of the mean height of all oak stump sprouts measured. These stump sprouts averaged 3.4 m tall at age 5, so a "successful" oak advance reproduction stem had to be at least 2.7 m tall. Eighty percent was chosen as the success criterion because nearly all oaks at least 2.7 m tall at age 5 were dominant or codominant. Based on this criterion for success and initial and 5-year measurements, we used logistic regression to develop equations to predict the probability of success for an individual oak stem of a given size (P5). The logistic regression equation is of the form:

$$P5 = \{1 + \exp[-(B_0 + B_1X_1 + \ldots B_nX_n)]\}^{-1}. \tag{1}$$

Regression coefficients are given in Sander _et al_. 1984. In addition to initial tree height and basal diameter, we used aspect and slope position to predict P5. These probabilities did not differ significantly by species ($P<0.05$) so the resulting estimates are for all four species combined.

The regression estimates showed that success probabilities increase with increasing initial height and ground diameter. In addition, probabilities were highest on southeast and northwest aspects and on middle slope positions. Initial size being equal, probabilities of success were lowest on northeast facing slopes and on lower slopes. Probabilities of success ranged from less than 0.01 for 0.3-m-tall trees of small diameter on lower slopes to 0.88 for trees 3-m-tall with large (6 cm) ground diameters on middle slopes of southeast or northwest aspects. In general these relations reflect a low likelihood of tree development where soil moisture is extremely favorable or unfavorable. High mortality and/or poor growth on droughty sites and severe competition on moist sites may account for the lower success probabilities.

We know how many dominant and codominant oaks are needed at age 20 to produce an adequately stocked stand, but our regression estimates (P5) only produce success probabilities to age 5. Therefore, we adjusted success probabilites for advanced regeneration at age 5 to success probabilities at age 20 (P20) by assuming a 99-percent annual survival rate from age 6 to age 20 based on earlier work (Sander 1972, Sander _et al_. 1976). Thus,

$$P20 = P5(0.99^{15}) = P5(0.86). \tag{2}$$

The resulting probabilities estimate the proportion of advance reproduction stems expected to be dominant or codominant at age 20.

From P20 we then determined the number of oak advance reproduction stems (n) required to produce, at probability 0.8 or greater, at least one codominant or larger stem at age 20 based on the following relation:

$$n = \log_e(1-0.8)/\log_e(1-P20). \tag{3}$$

This relation is based on the binomial probability distribution and

assumes trees attain "success" status independently of one another with equal probabilities (Johnson 1976).[2] The probability that one advance reproduction stem of a given size achieves dominance or codominance 20 years after final harvest at least 80 percent of the time is then 1/n. Expressed as a percent, 1/n is referred to as stocking value (SV). It defines the probable contribution of a stem to future stand stocking and can be used to quantify stocking on 5.5-m^2 plots (Table 1). To simplify field procedures, only the largest reproduction stem (i.e., the stem with the largest SV) is measured in each plot.

The average stocking value for a stand based on an inventory using 5.5-m^2 plots is the percent of the 1,818 (i.e., $.00055^{-1}$) unit growing spaces per hectare expected to produce dominant or codominant oaks at a mean stand dbh of 7.6 cm (about age 20). This percent must then equal or exceed 30 (i.e., (545/1818)100) for oak advance reproduction to be adequate and fulfill minimum future stocking requirements based on the 545 tree goal.

PREDICTING THE CONTRIBUTION OF OAK STUMP SPROUTS TO FUTURE STOCKING

The potential for sprouting from stumps of overstory oaks (trees $\geq$4.1 cm dbh) can be used to compensate for deficiencies in oak advance reproduction when evaluating the oak regeneration potential of a stand. Stump sprouts are the fastest growing oak component in new stands, and those of low origin usually develop into trees of acceptable quality (Roth and Hepting 1969).

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[2]Equation 3 was derived by letting:

S_n = the number of successful trees 20 years after final harvest out of n trees initially inventoried;

p = the probability that a single tree will be successful;

q = 1 - p.

The probability of having S_n = k trees out of n initial trees is given by the binomial distribution:

$$p(S_n = k) = \binom{n}{k} p^k \cdot q^{n-k}. \tag{4}$$

Note that $p(S_n \geq 1) = 1 - p(S_n = 0)$. (5)

Thus, if we want to determine the number of trees required to produce at least one successful tree 20 years hence with 80-percent probability, then substituting in (5):

$$0.80 = 1 - p(S_n = 0)$$

$$p(S_n = 0) = 0.20;$$

letting k = 0 in (4): $p(S_n = 0) = \binom{n}{0} p^0 q^{n-0}$

which reduces to: $p(S_n = 0) = q^n = 0.20$

$$n \cdot \log_e q = \log_e(0.20)$$

$$n = \frac{\log_e(0.20)}{\log_e q} = \frac{\log_e(0.20)}{\log_e(1-P20)}.$$

Table 1. Stocking values (SV)[a] for oak advance reproduction inventoried on 5.5-m^2 plots.

Size of tallest tree per plot		Aspect and slope position of plot								
Height class	Ground diameter class	Southwest			Southeast and Northwest			Northeast		
		Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower
m	cm	Plot SV in Percent								
<0.3	all	1	1	0	1	2	0	1	1	0
0.6	1	3	4	1	6	7	1	3	4	1
(0.31-0.90)	2	10	11	2	15	18	4	8	10	2
	3	20	23	5	29	34	8	17	20	4
1.2	1	8	9	2	12	14	3	6	8	1
(0.91-1.50)	2	16	19	4	25	28	6	14	17	3
	3	27	32	7	39	44	12	24	28	6
	4	40	45	12	54	60	19	36	41	11
1.8	1	16	18	4	24	28	6	14	16	3
(1.51-2.10)	2	26	30	7	38	43	11	23	27	6
	3	37	42	11	51	56	17	33	38	9
	4	48	53	16	62	68	24	43	49	14
2.4	2	40	45	12	54	59	19	36	40	10
(2.11-2.70)	3	48	53	16	63	68	24	44	49	14
	4	56	61	20	70	75	29	51	56	17
	5	62	68	24	77	82	35	58	63	21
3.0+	2	56	61	20	71	76	30	51	57	17
(2.71+)	3	60	65	22	75	80	33	55	61	20
	4	63	69	25	78	83	36	59	64	22
	5	66	72	27	81	85	38	62	67	24
	6	69	75	29	83	88	41	65	70	25

Narrow ridge tops ---------------------------
Level areas (<15 percent slopes other than ridge tops and bottoms) ------------------------------
Bottoms ---

[a]SV is the expected percent of 5.5-m^2 plots that will contain, at probability 0.8 or greater, at least one codominant or dominant stem at age 20. For a stand to be adequately stocked, SV averaged over all plots must equal or exceed 30 percent.

Factors shown to influence oak stump sprouting in a Missouri study include site quality and parent tree age and dbh (Johnson 1977). Sprouting frequency decreases with both increasing parent tree age and dbh but increases with increasing site quality. These relations were used to develop equations to estimate the percent of parent trees that will produce codominant or dominant black, white, and scarlet oaks at age 5. Data from Wendel (1975) and Johnson (1975) similarly were used to estimate percents for northern red oak. These percents then were adjusted for anticipated mortality to stand age 20 by assuming a survival rate of 99.25 percent per year for 15 years based on a 32-year stump sprout study (Roth and Hepting 1969).

Using these adjusted percents, we calculated values of n by using equation (3); we then used 1/n as the estimate of the percent of parent trees expected to produce, at probability 0.8 or greater, at least one dominant or codominant stem at age 20 (Table 2). For black oak and white oak, expected percents are shown by parent tree age, parent tree dbh, and site index. Age and site index information was not available for scarlet oak, so percents are given by diameter classes only. The latter values are averages for sawtimber-size stands in the Missouri Ozarks. Percents for northern red oak are based on data from parent stands in West Virginia that were 50 to 55 years old on site index 18.3 to 24.4 m, and from stands in Wisconsin that ranged from 70 to 110 years old on site index 15.2 to 21.3 m (Wendel 1975, Johnson 1975).

The minimum number of stump sprouts per hectare (N) required to compensate for deficiencies in advance reproduction is:

$$N = 545 - (\overline{SV}/0.055), \tag{6}$$

where $\overline{SV}$ is the mean stocking value for oak advance reproduction obtained from an inventory of advance reproduction (Table 1). This mean stocking value then can be compared to the expected number of stump sprouts to determine if advance reproduction plus stump sprouts will be adequate to replace the old stand. In practice, diameters of overstory trees can be measured on 1/50-ha plots (7.98-m radius) to facilitate calculating the expected number of stump sprouts per hectare.

APPLICATION

A complete guide is available for evaluating the oak regeneration potential of Missouri Ozark stands including appropriate inventory methods (Sander *et al.* 1984). In addition, software is available to help users calculate advance reproduction stocking values, expected numbers of stump sprouts, and the overall adequacy of the oak regeneration potential using stand inventory data (see SOFTWARE section).

The available software is designed to answer "yes" or "no" to the question: Is the oak regeneration potential of a stand adequate based on the predicted stocking of codominant and dominant oaks at stand age 20? However, this method of quantifying regeneration potentials could be extended to predict the potential contribution of any species in any crown class at any future age. The method also is potentially applicable to any ecosystem under even-aged management in which the composition and structure of the advance reproduction and the overstory can be used to quantify the regeneration potential of a stand.

Preliminary tests of the method using data from six 5-year-old Missouri Ozark stands correctly predicted stocking adequacy in five of the six stands. Continued measurement of the trees in the original dataset will provide more reliable 20-year estimates of success probabilities and, in turn, more reliable regeneration stocking guides.

Table 2. Expected percent of stumps that will produce, at probability 0.8 or greater, at least one codominant or dominant stem at age 20.

Species	Site index[a]	Dbh class	Age of parent tree (years) 40	60	80	100	All ages
	m (ft)	cm					
Black oak[b]	15.2 (50)	4-13	36	34	32	30	--
		14-29	13	11	10	8	--
		30-41	6	5	4	3	--
		42+	--	2	2	1	--
	18.3 (60)	4-13	47	45	42	40	--
		14-29	16	15	13	12	--
		30-41	7	6	5	4	--
		42+	--	3	2	2	--
	21.3 (70)	4-13	61	59	56	54	--
		14-29	21	19	17	16	--
		30-41	10	8	7	6	--
		42+	--	5	4	3	--
White oak[b]	15.2 (50)	4-13	47	25	12	5	--
		14-29	18	10	6	3	--
		30-41	6	4	3	2	--
		42+	--	2	1	1	--
	18.3 (60)	4-13	63	38	19	8	--
		14-29	26	16	9	5	--
		30-41	9	7	5	3	--
		42+	--	3	2	2	--
	21.3 (70)	4-13	81	55	31	15	--
		14-29	36	25	16	9	--
		30-41	15	11	8	6	--
		42+	--	5	4	4	--
Northern red oak[c]	18.3+ (60+)	4-13	86	86	49	49	--
		14-29	86	86	46	46	--
		30-41	86	86	38	38	--
		42+	--	86	24	24	--
Scarlet oak[d]	15.2+ (50+)	4-13	--	--	--	--	46
		14-29	--	--	--	--	96
		30-41	--	--	--	--	46
		42+	--	--	--	--	10

[a] Index age is 50 years.
[b] Values are based on data from Johnson (1977).
[c] Values are based on data from Wendel (1975) and Johnson (1975).
[d] Values by parent tree age are not available. Values given are means for sawtimber-size stands of various but unknown ages.

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Program Name: ADVREGEN

Programmer: Ivan L. Sander

Hardware and Software Requirements:
- Computer model .... Data General Eclipse
- Operating system .... AOS-VS
- Printer required .... No
- Additional information

This program requires English units of measurement. Required input includes:
(a) an oak advance reproduction list including tree heights and basal diameters obtained from an inventory of 1/735-acre (5.5-m^2) plots plus the aspect (NE, SE/NW, or SW) and slope position (upper, middle, or lower) of each plot;
(b) a list of the diameters (dbh) of overstory oaks by species obtained on 1/20-acre (0.02-ha) plots, mean stand age, and site index.
Output includes the mean stand stocking value for oak advance reproduction, expected number of oak stump sprouts per acre, and a "yes" or "no" answer to oak regeneration adequacy.

Program Available From: North Central Forest Experiment Station
1-26 Agriculture Building
University of Missouri
Columbia, MO 65211

Media: Printed listing

Cost: None

Program Name: OAKREGEN: HP41C

Programmer: Robert Rogers

Hardware and Software Requirements:
- Calculator model .... Hewlett-Packard HP41CV or HP41C with four memory modules added (1,883-byte program)
- Printer required .... No
- Additional information

This is a programmable calculator version of ADVREGEN that also requires English units of measurement.

Program Available From: The above address

Media: Printed listing

Cost: None

PLANT: A MODEL FOR ARTIFICIAL FOREST REGENERATION IN ONTARIO[1]

BIJAN PAYANDEH[1]

ABSTRACT. A simulation model was developed to help managers in Ontario solve forest renewal problems. The model treats the regeneration process as three separate, but interdependent phases of: 1) stock production, 2) storage, and 3) plantation management. During each phase, growth and survival of seedlings are simulated according to empirical submodels reflecting the effects of various biological factors as well as management options. Large data sets from several greenhouse/ nursery operations and experimental plantations established in northern Ontario were used to construct predictive models. Such regression models were derived by first identifying factors affecting stock production and plantation performance via stepwise regression procedures, and then developing nonlinear models expressing seedling growth and survival as functions of time, management options and silvicultural practices. The model simulates various regeneration options according to the users choice. It compares and optimizes the results based on Regeneration Cost Effectiveness Index. RCEI in effect combines the cost of production with growth, survival and the quality of the resulting "free-to-grow" stand. The model is written in FORTRAN and BASIC languages.

INTRODUCTION

Forest renewal is the most pressing problem facing forest managers in Canada [see Fellows (1986) for a historical review]. Because of the impending wood supply problems and the backlog of cutover areas, federal and provincial agencies and the forest industry are obliged to invest increasingly large sums of money annually in forest regeneration.

Recent symposia on forest regeneration (Anon. 1981, Scarratt et al. 1981, Mroz and Berner 1983) effectively illustrate the need for synthesizing information on forest renewal. In Ontario, artificial forest regeneration practices have been studied for many years. Investigations have ranged from biological factors to economic considerations. Much is known about the individual factors affecting seedling survival, growth and production costs. However, researchers have not completely addressed the interrelationship of the important identified factors. Therefore, there is a strong need to synthesize the knowledge currently available in order to understand the regeneration process as a whole. Such an understanding would be facilitated by the development of a management-oriented computer simulation model. A research study to develop such a model for Ontario is currently underway at the Great Lakes Forestry Centre. The intention of this study is to fully integrate the biological factors with economic components of the regeneration systems. The objective of this paper is to describe the model

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development to date including the identification of factors affecting plantation performance.

MODEL DEVELOPMENT

The preliminary stage of model development requires exhaustive review of literature of the quantitative information (data) available on each of the candidate species, black spruce *(Picea mariana* [Mill.] B.S.P.), white spruce *(P. glauca* [Moench] Voss) and jack pine *(Pinus banksiana* Lamb.) from seed source selection to 20 years following stand establishment. The next step consists of the identification of critical factors affecting survival and growth of the candidate species during the regeneration period.

For the purpose of model construction, the entire process of artificial regeneration is viewed as a system beginning with seed source selection and ending with successful plantation establishment. Three major phases are considered here in the regeneration process based on changes in environmental factors affecting the seedling growth and development. These phases are: 1) seedling production, 2) seedling storage and 3) plantation management. Movement from one phase into the next phase entails a major change in environmental influence on the seedlings. The degree of control over the environment of growing seedlings ranges from nearly complete control in the storage phase to very little control in the plantation phase.

Phase I begins with the input of greenhouse/nursery management options. This step is followed by the simulation of growth and mortality for the length of time specified by the management inputs. The seedling then is assessed in terms of biological potential and cost. A return to the beginning of Phase I then allows additional growth periods in the greenhouse environment or the possible transplanting of seedlings in the nursery. The model continues into Phase II where storage will be specified and seedling potential along with cost estimates are determined. As in Phase I, there is an opportunity to change the storage environment and reassess the seedlings. A change in seedling potential within this Phase is reflected in the potential for seedling growth and mortality.

The final phase begins with input of plantation site characteristics, site preparation, season of planting, planting methods and competition controls. Seedling growth and mortality for the first growing season is then simulated and the development of the plantation is assessed biologically and economically. The next growing season begins with a return to the input of selected competition control measures, and the subsequent simulation and assessment steps. The plantation is considered "established" or "free to grow" after a number of growing seasons have been simulated as specified by the input as a management option. The degree of success in plantation establishment is determined from the biological potential and economic consideration.

Within each phase of the model a complete decision tree outlining the different management options in the regeneration process is developed. Such regeneration alternatives are simulated in a parallel manner throughout the regeneration process. Where treatments are applied their

effects will be incorporated by input estimates or through appropriate submodels. All associated costs are properly analyzed and accumulated. Once all regeneration systems in question are simulated, the results are compared and ranked based on the following index:

$$RCEI = C/(\bar{H}\ S\ Q) \qquad (1)$$

where, RCEI is defined as Regeneration Cost Efficiency Index, C is the total cost of production, $\bar{H}$ is average plantation height, S is survival rate and Q is average quality index. The model reports the results for the five top ranking alternatives based on the above RCEI.

MATERIALS AND METHODS

The stock production data used in Phase I were obtained from four greenhouse/nursery operations located in Kirkland Lake, Thunder Bay, Dryden and Midhurst, Ontario. They included sample identification, date of measurement, age of seedlings, density, height (cm), root collar diameter, root, shoot, and total dry weight and root-shoot-ratio. The container stock data included: species, container size and type, growing medium, dates of sowing, germination, and shipping. Seedling ages were recorded weekly. Shoot height and root collar diameter were measured to nearest 0.1 mm. The few data used for Phase II came from the literature. The bulk of the data for Phase III are based on two major outplanting studies described elsewhere (Wood and Dominy 1985, Sutton 1987).

Preliminary analyses of data have been reported earlier by Payandeh and Wood (1987). In brief, stepwise regression analysis was used to screen out factors affecting seedling survival and growth. Both continuous and categorical variables were used as predictors. Variables identified as significant factors affecting seedling performance were then used to develop appropriate nonlinear regression models. The models expressed seedling survival and total height as exponential decay and exponential functions of time and such variables, respectively.

ANALYSIS AND RESULTS

Preliminary analysis of the growth progression and container stock production data indicated considerable difference and variability in height growth associated with species, stock type and whether the stock was over wintered or not. Therefore, separate regression equations were developed for each group, i.e, per species/stock type/overwinter. Even within each group, seedling age or ADD (Accumulative Degree Day) accounted for less than 30% of the variability in seedling height. However, root-collar diameter and seedling height were highly correlated in every case. Therefore, seedling height was expressed as a function of diameter and age as:

$$H = b_1 D^{b_2} e^{(b_3 + b_4 x_1 + b_5 x_2)/A} \qquad (2)$$

where, H is seedling height (cm), D is seedling root collar diameter (mm), A is seedling age (weeks), x_1 is age (or number of growing

seasons) before transplanting, x_2 is age after transplanting, b's are parameters of the model and e is the base of natural logarithm.

The R^2 value for various species/planting stock combination for the above model varied between 0.84 and 0.97. Many of the data showed survival rates for bare root and container stock of nearly 100%; occasional samples showed up to 4% mortality. Therefore, a generalized survival function was developed on the pooled data set as follows:

$$S = b_o + b_1 e^{b_2 A} \quad (3)$$

where, S is survival and other variables are as defined earlier.

Preliminary analysis of the outplanting data indicated that total height and height increment may be predicted with fewer variables and more precisely than the survival. Of the three candidate species jack pine survival and height increment may be predicted more precisely than the other two species and its total height better than that of black spruce. Black spruce survival was the most heterogenous response variable where six predictor variables accounted for about 56% of its variability. The most significant single predictor variable was plantation age which accounted for up to 30% of the variability in survival and up to 63% of the variability in total height (Payandeh and Wood 1987). Since site factors and planting stock characteristics are subject to management manipulation, the following two generalized models were used to express seedling survival rate and total height following outplanting:

$$S = b_o + b_1 e[b_2 + b_3 Z_1 + b_4 Z_2 + \quad b_p Z_q)A] \quad (4)$$

$$H = b_o + b_1 e[b_2 + b_3 Z_1 + b_4 Z_2 + \quad b_p Z_q)/A^{b_p}] \quad (5)$$

where, Z's are dummy variables designated the value of 1 or 0 depending on whether the case belongs to that category or not.

Factors included in the above models were: site preparation (mechanical, chemical or prescribed burn), weed control (herbicide application), stock type (bare-root or container), transplanting, container size, and planting season.

Table 1 summarizes the preliminary equations expressing survival and total height as functions of site factors, and planting stock characteristics for black spruce, white spruce and jack pine. All equations produced very good fit considering the variables included in the model. Model (4) did not prove satisfactory for jack pine survival, perhaps because of the peculiarity in the data set. However, a modified form of model (4) produced acceptable results.

MODEL APPLICATIONS

The application of the model is demonstrated here by describing an example in detail. The main objective of the example is to show the model capability and flexibility and not to recommend one regeneration method over another one. The input estimates were obtained mainly from

Table 1. Nonlinear regression equations for growth and survival of black spruce, white spruce and jack pine in Ontario.

Species	Regression equation	R^2	SEE
Black spruce	S = 0.32 + 0.68e [(-0.052 - 0.002SA - 0.03SB + 0.006WC + 0.034CS + 0.193TR - 0.173ST - 0.03PS)*A]	0.58	0.09
	H = 16.72 + 466.4e[(-7.05 + 0.018SA + 1.17SB + 0.76WC + 0.15CS + 0.45TR + 0.71ST - 0.39PS)/A**0.531]	0.78	8.03
White spruce	S = 0.47 + 0.53e[(-0.21 - 0.007SA - 0.085SB + 0.104WC + 0.06CS - 0.00003TR - 0.00002ST - 0.00004PS)*A]	0.51	0.08
	H = 12.89 + 204.6e[(-6.29 + 0.03SA + 0.75SB + 0.93WC - 0.54CS + 0.22TR + 1.57ST - 0.5PS)/A**0.52]	0.71	6.82
Jack pine	S = 0.36 + 0.56e[(-0.03 - 0.08WC - 0.013ST + 0.072PS)*A] + 0.054SA - 0.005SB + 0.005SB + 0.16CS + 0.05TR	0.42	0.10
	H = 14.6 + 7725e[(-5.83 - 2.19SA - 2.69SB - 0.95WC + 0.33CS + 2.22TR + 0.93ST - 0.77PS)/A**0.378]	0.97	7.83

where, SA and SB are mechanical and chemical site preparation, WC is weed control, CS is container size, TR is transplanting, PS is planting season, ST is stock type, and other variables are as defined earlier.

greenhouse/nursery and plantation records, recent literature, and several foresters from the Ontario Ministry of Natural Resources.

The example attempts to evaluate plantation performance for black spruce and white spruce bareroot and container stock. Two seed sources are assumed for black spruce where genetically improved stock is estimated to grow about 30% greater than the local one at an additional cost of \$15.00/1000 seedlings. Two classes of bareroot stock (1.5 + 0.5 and 2.0 + 0.0) and medium size container are grown at a cost of \$15.00 and \$10.00/1000 seedlings, respectively. No greenhouse, nursery or winter storage are considered in this example. In the case of white spruce, however, only small size container from local seed source is assumed at a cost of \$10.00/1000 seedlings. Black spruce seedlings were to be planted in early summer on a moderately productive site (site class 2) prepared in two ways: by shear blading and prescribed burning, at a cost of \$120.00 and \$100.00/ha, respectively. The cost of hand planting was assumed to be \$300.00/ha. In the case of white spruce container stock, the assumption was made that a highly productive (class 1 site) would be prepared by prescribed burning at a cost of \$100.00/ha and machine planted in late spring at a cost of \$230.00/ha. No herbicide application or stand tending was considered in any of the nine alternative regeneration systems of this example.

The output of the example run for the five top ranking regeneration systems is summarized in Table 2. The top portion of this table provides statistics such as RCEI ($/m), optimum RCEI' and age (yr.) i.e., age at which RCEI is minimum, survival (%), total height (m), quality index and total production cost ($/1000). For this example, the RCEI (at age 20) ranged from $0.97 to $1.05, while the optimum RCEI, i.e., lowest index at a given age, ranged from $0.73 to $0.83 for optimum ages of 9 to 11 years, respectively.

Table 2 also summarizes the main features of the five top ranking regeneration alternatives for each of the three phases. It indicates that the best ranking alternative for the example is an early summer planting (by machine) of genetically improved black spruce container stock (medium size) on prescribed burn and moderately productive sites (site class 2). The second best alternative is manual spring planting of local white spruce containers (small size) on prescribed burn, highly productive sites. The remaining alternatives may be interpreted in a similar fashion.

The model also optionally produces the plotting of total height, survival and the RCEI for the five best regeneration alternatives over age. The latter graph is of particular interest as one may easily locate the optimum RCEI and its associated age as the minimum point on each curve. Also the magnitude of differences between the relative performance of the five best alternatives is readily apparent.

SUMMARY AND CONCLUSIONS

"PLANT" is a management-oriented computer model which simulates the growth and mortality of seedlings throughout the regeneration process from seed source selection up to 20 years following outplanting. The effects of some critical biological factors and management options are considered by expressing seedling growth and survival submodels as functions of such variables. For many factors, however, sufficient information (data) is not available to be directly incorporated in the model. Nevertheless, the model allows inputting the effects of such variables as a simple "coefficient" (±%, i.e., increase or decrease in performance as compared to the norm) by the user.

The model simulates various regeneration systems based on a decision tree approach and the users specifications. It compares, ranks and optimizes the alternatives so generated based on an index combining the total cost of production, growth, survival and the quality of the resulting stands. It summarizes up to five of the best ranking alternatives for the user's examination both in tabular and graphical forms.

Considerable work remains to be done in data collection, submodel construction, modification, model validation and verification. In particular, expression of seedling quality and its effect on growth and survival needs major improvement and validation. Introduction of new and improved container stock types require data collection and submodel development. Similarly, much information is needed on recent options for site preparation, planting equipment, weed control and stand tending to be incorporated in the model.

Table 2. Summary of the top five alternative regeneration systems for the example.

Item	Rank (1)	(2)	(3)	(4)	(5)
RCEI $/m	0.97	0.98	1.04	1.04	1.05
Optimum RCEI $/m	0.73	0.78	0.78	0.82	0.83
Optimum age (yr)	9	10	9	10	11
Survival (%)	68.92	68.21	67.25	69.44	70.65
Total height m	3.84	2.86	3.80	3.50	3.40
Quality index	1.07	1.04	1.07	1.04	1.06
Production cost ($/1000)	2746.83	1988.26	2843.38	2628.72	2673.53
Stock Production					
Species:	Sb	SW	Sb	Sb	Sb
Seed source:	Plus tree	Local	Plus tree	Local	Local
Stock type:	Container	Container	Container	Container	Container
Container size:	Medium	Small	Medium	Medium	Medium
Storage	-	-	-	-	-
Winter storage:	-	-	-	-	-
Winter storage treatment:	-	-	-	-	-
Plantation Management					
Site class	Two	One	Two	Two	Two
Site preparation	Burn	Burn	Mech.	Burn	Mech.
Planting season	Summer	Spring	Summer	Summer	Summer
Planting method	Machine	Hand	Machine	Machine	Machine
Competition control	No	No	No	No	No

Two versions of "PLANT" are being developed further; one in FORTRAN 77 standard and one in Apple BASIC. Both are user-friendly, the latter being a fully menu driven program.

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REGENERATION MODELLING AND ITS MANAGEMENT APPLICATIONS

PENTTI K. RÄSÄNEN[1)]

ABSTRACT. In deciding on how to regenerate a forest site a manager must determine the regeneration method on the basis of biological, technical, economic and environmental consideration. Regeneration comprises a number of successive, frequently interconnected operations, events and phenomena in a way that a change in one will have an impact on the others. For better regeneration performance, improvements in steering the whole "operational chain of reforestation" is needed. Answers can be sought from many disciplines; e.g. modelling has been done with both theoretical and very practical approaches. So far, however, modelling has not been very successful in integrating the complex reality of the regeneration process. Expert systems seem to have promise for advancing modelling. Also experimental research for producing data on the distribution of environmental factors and results would be still needed.

INTRODUCTION

The regeneration phase in the development of forests comprises a number of successive, frequently interconnected operations, events and phenomena, which occur over a period of years - even decades in the polar and temperate zone conditions. The bulk of silvicultural costs are caused by regeneration, the outcome of which determines future stand development, growth and yield. The study of regeneration is one of the most central and most difficult questions in silviculture (Räsänen 1981). Answers can be sought from many disciplines.

One of the focal areas has been field practice. Work has consisted of gathering all relevant information to improve forest regeneration success, especially in artificial regeneration. The information has been collated into a new form of prescriptions and called "operational chains in reforestation".

A separate group of Finnish studies to verify and improve regeneration results is composed of many regeneration inventories (Räsänen et al. 1979a, 1985). Inventory studies show that regeneration results were

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generally satisfactory and slightly improving in the course of time though they varied greatly from case to case. Planting had produced the best stands of young trees; still, for various reasons such as insufficient tending, a large part, about 25 % of plantations were found to be understocked (Räsänen et al. 1985). Earlier results could be even less adequate. There really is reason to try to progress with regeneration practice.

THEORETICAL BASIS

Forest regeneration is modeled for management applications in order to improve regeneration in practical scale work, in order to improve all man's activities, and take into account all factors of nature sufficiently to get fully stocked, healthy, well-growing, good quality plantations at reasonable cost. But how to take into consideration the ecosystem: climates, soils, tree species, other plants, animals etc.? How to assess the "operational chain" of reforestation, the possible alternatives? In any one regeneration case there are hundreds of relevant "chains", management alternatives, composed of these two main factor groups. The first step obviously is to gather and maintain a database, which makes possible the modelling effort and the use of the model in practice. There is a lack of reliable, detailed data for large part of the regeneration process; especially data on the distribution of environmental factors and results would be needed. Out-put data is scarce and sporadic, and discontinuous rather than continuous. The continuity between distinct results must often be generated with a best-guess method.

Situations, where modelling could be a good decision making tool are just prior to the regeneration process in planning, implementation, control, and in monitoring the performance of planted trees.

Usually modelling help is desired before regeneration. In fact, that phase is the most important from the point of assessing the regeneration process as a whole. That is also when the main decisions are made, for instance the selection of the site preparation method and the tree species. However, regeneration is a series of decisions and activities, and for each of them, modelling could be needed. Therefore we should develop flexible models which can be used dynamically in different phases, or separate models for subsequent phases of the regeneration process. For research purposes the models are specialized by physiological process, such as photosynthesis, transpiration, stress tolerance, or even more detailed models based on a combination of environmental variables, and the development and growth of plant organs. Theoretically, there is no reason why we could not precisely model the

regeneration process. The idea to "fully" regulate the process may be fascinating (Räsänen 1981). Modelling is hardly today limited by e.g. computer capacity . At present, however, an attempt to perfectly model regeneration is probably neither possible, because of lack of knowledge, nor economically desirable. In fact, both economic and biological models of regeneration are in their "infancy" (Räsänen 1981, Gordon and Duryea 1985), and many approaches taking regeneration as a "system" are likely to result in improved regeneration.

The management of complex phenomena in almost all fields of life - also in forestry research and forestry - have been tackled by means of modelling, recently by systems analysis and systems engineering. For some reason there has been little reforestation research based on the systems approach. This thinking can be simplified by distinguishing two processes: planting stock production and artificial regeneration (Räsänen 1980). "Essential to the system of growing forest tree seedlings is the fact that the forest tree seedling being raised, as well as its development and growth, can be studied as a natural process, a primary system. <u>The seedling development process</u> and the goal-directed human activity (i.e. the growing of seedlings) which is an operational whole consisting of information gathering, planning, implementation, and control, are studied as a secondary process, <u>a seedling growing process</u>" (Räsänen 1981). The primary system can be seen as a subsystem of the secondary one. The secondary system can further be observed in phases, subsystems, such as seed germination, the protection of seedlings during transport, and the planting shock phase (Räsänen 1980).

APPLICATIONS

A holistic scope has generally been accepted in Finland since the late 1960s, for regeneration research and for revising regeneration prescriptions. There was much talk about whether this should be the domain of practical decision-making duty only, rather than a "real" research problem. Regeneration research in Finland was intensive, but the new approach was not adopted. Practical forestry organizations made numerous initiatives to promote a holistic research approach that covers the entire regeneration phase system, rather than the more traditional research approach of focusing on individual factors of regeneration (Räsänen et al. 1979b). Those organizations developed their own separate "operational chains in reforestation", in the late 1970s and early 1980s.

Tehdaspuu Ltd started first to use their new prescriptions, "chains" in 1976. The National Board of Forestry finished its operational chains for state forests in 1978 and Central Forestry Board Tapio gave

its first version of the chains for private forests in 1980. Tapio made a second version already two years later, and a new version is now being made. In every organization, a huge job was done in preparing the chains.

The basic structure of chains made by the different organizations is rather similar, but the the details vary greatly. Regeneration sites are grouped into classes by those site factors with the greatest effect on regeneration performance. For each group, the best alternative or alternatives have been shown for every action commonly needed in that site. All sites (groups) and action alternatives have been gathered into one scheme, giving a general view of the chains. Supplementary prescriptions give more detailed quidance. Some companies, which so far have not put their prescriptions into the form of chains, however, emphasize the need to be holistic.

Climatically Finland is divided into five zones. These zones are also the basis for regeneration chains. All mineral soil sites including their slightly wet varieties are combined under the system. The National Board of Forest has also prepared separate chains for swamps. Central Forestry Board Tapio has also prepared chains for abandoned fields to be forested.

Tehdaspuu Ltd classifies upland regeneration sites into only two groups by their fertility. The Vaccinium site type and less fertile types are one, and the Myrtillus site type and more fertile types another group (for site definitions see Cajander 1949).

On the basis of "difficulty of regeneration" factors each of those two groups is divided, the former into eight subgroups (A-H, Annex 1), and the latter into nine subgroups. These 17 subgroups have been considered sufficiently homogeneous to recommend a distinct chain for each of them. Often there are two or three priorized alternatives. The chains of Tehdaspuu Ltd have been concentrated to a "basic solution" only. For instance, "site preparation: furrowing, tree species: Scots pine, planting stock: containerized, peat pot Fp-620, planting tool: Pottiputki-planting tube", comprises one chain.

There are altogether 24 chains. Five soil texture classes are the main factor in determining the subgroups. Other factors are: stoniness, swampiness, thickness of the raw humus layer, susceptibility to summer frosts, grass and herbaceous competition, brush competition, and the amount of fresh slash.

The National Board of Forestry classifies upland regeneration sites into three groups by their fertility. Two of these groups are further divided into moraines (85 % of forest soils in Finland) and assorted (sandy

and loamy) soils, these in turn by their stoniness, thickness of raw humus layer and swampiness. There are six subgroups in the lowest fertility group, seven in the middle group and four in the highest fertility group, 17 regeneration site groups altogether. For every group there are one to three priorized working method alternatives, for every reforestation measure.

The managers build the chain, case by case from those alternatives. Every year, average costs are given to the manager for help in calculation. Chronologically these chains extend from the regeneration cutting phase to the tending of the sapling stand.

The reforestation chains used in private forestry are similar to the one described above. There are five fertility classes, and altogether 21 subgroups according to site factors. As mentioned earlier, the prescriptions for private forestry are under revision.

Certainly there is a lot of research, which has had the same goal as practical prescriptions. However, there are few studies focusing on the whole regeneration process. They are most fruitful in a team, where many forest research sectors are represented, and also include systems engineers and mathematicians. In Finland the first study of this scope was published in 1979 (Räsänen et al. 1979a). We started model building from a decision tree for a case representing the artificial regeneration of Scots pine in central Finland, on a typical pine site type (VT). The decision tree was a collection of normal reforestation activities. Survival at the end of every branch of the decision making tree was assessed, and the age of the plantation on reaching the "free-to-grow-phase" (a dominant height of five meters).

The former approach has been enlarged, details added (Parviainen and Lappi 1983), and it has been the basis for a micro computer application (Parviainen et al. 1984). Another branch of the study has been developed by Kaila and Hämäläinen (1985). Also their model is micro computer aided. The immediate purpose of this project has been to get a holistic planning tool for forest industry owned forest. The most interesting innovation in the model is the possibility to aggregate and review the results of artificial regeneration after three subsequent phases: the site preparation phase, the early (five year) phase and free-to-grow -phase. Both of these applications are in trial use.

DISCUSSION

Many other countries in addition to Finland suggest regeneration modelling based on the whole (e.g. Boyd & Winjum 1979, Eriksson 1981, Belli 1986). Numerous, if not all are regeneration prescriptions, with an obvious effort to ensure the end results (e.g. Cleary &

Kelpsas 1981, Coffman 1982, Haymond 1982, Jordan & Balmer 1982). The scarcity of detailed knowledge, especially of the costs and benefits of alternatives and the enormous quantity of information, its complexity and partly "softness", have so far limited research efforts and their functioning management applications to a minimum.

Something has been achieved, however, after using "operational reforestation chains" for 7...11 years. At least every forester, forest technician and foreman planning and leading reforestation work is aware of the "new" holistic thinking. A decisive part in carrying out the improved regeneration system is played by the more than 300 000 Finnish forest owners. Their training and guiding is a continuous challenge to forestry specialists.

The chains developed by the different organizations differ greatly from each other, because they are "first round chains" with only a limited research basis, and because the owners' objectives vary, resulting in different decision making. It must be emphasized that the chains are developed to improve regeneration by linking together compatible actions at the right moment, from the point of view of the totality of the regeneration process. The chain reflects generalized knowledge at a given decision-making point, but activities are reviewed annually on the basis of information about actual results.

For improving regeneration practices and results, better technology and rising human know-how are required for the development of the next generation "operational reforestation chains". Without priority order some research and development topics are:
1. regeneration information systems, and linking them to mapping and other forestry information systems,
2. initial height growth and survival distributions in different regeneration situations,
3. competition impacts of scrub vegetation,
4. interaction between genetically superior planting stock x site preparation intensity, and
5. algorithms and submodels as part of a holistic regeneration model.

Now that some functioning system models have been made and tested,proper research on the operational chains can start. Special promise seems to be given by the systems approach, particularly systems engineering and the so-called expert systems. Their application into regeneration research is only just beginning, but they may represent the utmost future contribution to regeneration modelling. These methods offer the possibility of providing a practical means of communication between researchers and forest managers. And good cooperative work between these two specialist groups is extremely important.

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REFORESTATION RECOMMENDATION, mineral soil sites

Forest site type	Raw	CHARACTERISTICS OF THE SITE: SOIL: Gravel and sand	Coarse moraine	Fine moraine	Silt, loam	Clay	Very stony	Not sensitive to frost	Swampy	Much fresh slash	Ground vegetation: Scant	Moderate	Dense	No coppicing	Raw humus less than 5 cm	Recommended chain (Number of the chain): Primary	Secondary	Only if compulsory
VT and poorer and equivalent site types in Kainuu and East Bothnia	A	x	x				x				x			x	x	1^s,2^s	12,14	
	B			x								x			x	11,4*	14,15	5*
	C			x	x				x	x		x				7,3*	9,10	5*
	D	x									x			x	x	4	12,14	5
	E		x				x				x				x	11,4*	12	16,5*
	F			x	x				x	x			x			6	7	
	G				x							x			x	13	11	
	H				x				x			x				8	7,10	
MT and more fertile and equivalent site types in Kainuu and East Bothnia	I		x	x	x							x			x	11	6,10	16
	J		x	x	x				x	x		x				6	10	16
	K		x	x	x		x					x			x	11		16
	L			x	x			x					x		x	18	17	19
	M			x	x	x		x	x	x			x			17		19
	N			x	x		x	x					x		x	18		19
	O			x	x				x	x			x			20		22
	P			x	x		x						x		x	21		22
	R				x	x			x	x			x			23		24

x = yes
empty square = insignificant or negative
* = applicable mainly north of the line Lieksa-Iisalmi-Oulu
s = assumes that stand capable of seeding

Where soils subject to upheaval during spring thaw, barerooted stock planted in the spring and potted stock by the end of June

No	OPERATIONAL CHAINS OF REFORESTATION
1	Patch scarification or disc trenching Scots pine, natural regeneration
2	No site preparation, Scots pine, natural regeneration. Only easily regenerating sites
3	Furrowing , Scots pine, direct seeding
4	Patchel scarification, Scots pine, direct seeding
5	Hoe scarification, Scots pine, direct seeding
6	Furrowing, Scots pine, transplanted bare-root stock, planting with hoe
7	Furrowing, Scots pine, (untransplanted) bare-root seedlings, planting with hoe
8	Furrowing, Lodgepole pine, (untransplanted) bare-root seedlings, planting with hoe or peat pot Fp 620 seedlings, Pottiputki-planting tube
9	Furrowing, Scots pine, paperpot Fh-408 or peat pot Fp 615 seedling, planting tube
10	Furrowing, Scots pine peat pot Fp 620 seedlings, Pottiputki-planting tube
11	Patch scarification or disc trenching, Scots pine, transpl. bare-root stock, hoe plant
12	Patch scarification or disc trenching, Scots pine, (untranspl.) bare-root seedlings, hoe planting
13	Patch scarification or disc trenching, Lodgepole pine, (untranspl.) bare-root seedlings, hoe planting
14	Disc trenching, Scots pine, paper pot Fh-408 or peat pot Fp 615 seedlings, planting tube
15	Patch scarification or disc trenching, Scots pine, peat pot Fp 620 seedlings, planting tube
16	Hoe scarification, Scots pine, transplanted bare-root stock, hoe planting
17	Furrowing, Norway spruce, transplanted bare-root stock, hoe planting
18	Patch scarification or disc trenching, Norway spruce, transpl. bare-root stock, hoe plant
19	Hoe scarification, Norway spruce, transplanted bare-root stock, hoe planting
20	Furrowing, Silver birch, bare-root seedlings, hoe planting
21	Patch scarification or disc trenching, silver birch, bare-root or potted seedlings, hoe planting
22	Hoe scarification, Silver birch, bare-root or containerized seedlings, hoe planting
23	Furrowing, Lodgepole pine, transpl. bare-root stock, hoe planting
24	Hoe scarification, Lodgepole pine, transplanted bare-root stock, hoe planting

PERFORMANCE OF A SOIL PRODUCTIVITY INDEX MODEL USED TO PREDICT SITE QUALITY AND STAND PRODUCTION

M. R. Gale and D. F. Grigal[1]

ABSTRACT. A soil productivity index model, originally developed for white spruce (Picea glauca (Moench) Voss), was tested for four other northern tree species. The model uses soil horizon characteristics, climate and topography as they relate to a species' optimum vertical root distribution and calculates a site productivity index (PI). Datasets for red pine (Pinus resinosa Ait.), trembling aspen (Populus tremuloides Michx.), jack pine (Pinus banksiana Lamb.), and red maple (Acer rubrum L.) were used to test the model's performance in predicting site index and aboveground production. In most cases, PI explained significant variation in site index (SI), volume, and mean annual increment. Comparable results between PI and SI were obtained for the red pine and jack pine datasets when used in a Schumacher-type equation predicting volume and mean annual increment with age. Equations with SI were slightly superior to those with PI for aspen, and were markedly superior for red maple.

INTRODUCTION

Numerous studies have examined the relationship between soil properties and aboveground productivity (Carmean 1975). Most of these studies have used regression techniques to predict site quality using individual soil properties. However, problems with multicollinearity and "regionality" of regression techniques have limited their results and their applicability to other areas (McQuilkin, 1976; Stone, 1978). Probable interactions between individual soil and site properties have also been generally ignored (Stone, 1978). Because of these problems, some researchers have redirected their efforts towards developing models that are less dependent on empirical data from one geographical area and are more "process-oriented", relating the effects of soil properties and climate on a tree's morphological and physiological characteristics (Landsberg 1986).

One such empirical yet "process-related" model is the soil productivity index (PI) model (Pierce et al. 1984; Gale 1987) which integrates soil and site characteristics and their relationship to root growth and to the vertical root distribution of a tree. The model is based on the premise that a tree species is genetically predisposed to a certain vertical root distribution and under optimum soil/site conditions will always produce the same proportional rooting pattern. If soil or site properties are limiting, however, the proportional root distribution will change, negatively affecting the shoot. Because of the intimate interaction of

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root and shoot development, models that incorporate root responses to their environment can be important tools in predicting potential site productivity. Accuracy of such models, however, must be assessed. The objectives of this study were to 1.) refine the PI model for several northern tree species (red pine, trembling aspen, jack pine, and red maple, 2.) determine if there are significant relationships between PI, site index, and stand production (volume/biomass and mean annual increment), and 3.) determine if comparable results can be obtained using either PI or site index to predict stand production with age.

METHODS

Four datasets, red pine (Alban 1976), trembling aspen (Stoeckeler 1960), jack pine (Pawluk 1957), and red maple (Haag 1987), were used to test the use of PI in predicting site index, volume/biomass, or mean annual increment. The red pine, aspen, and jack pine datasets contained volume estimates while the red maple dataset contained biomass estimates. All stands were of natural origin. Measurements from the jack pine dataset were on pure, even-aged stands while measurements from the red pine, red maple, and aspen datasets were from even-aged stands with some admixture of other species. At least 75 percent of the species composition for these stands, however, were of the dominant species. For the aspen and jack pine datasets soil properties were measured for each soil horizon. On most plots for the red pine dataset, composite soil properties were measured for two soil depths (0-25cm and 25-100cm). For the red maple dataset, properties of some soil horizons were missing; they were described as having the same characteristics as the horizon below them.

THE SOIL PRODUCTIVITY INDEX (PI) MODEL

The PI model is of the form:

$$PI = \sum_{i=1}^{r} ([A \times C \times D]^{1/3} \times WF)_i \times [S \times Cl \times WT]^{1/3} \qquad (1)$$

where A is the horizon sufficiency rating for potential available water, C is the horizon sufficiency rating for bulk density, D is the horizon sufficiency rating for pH, S is the site sufficiency rating for percent slope, Cl is the site sufficiency rating for climate, and WT is the site sufficiency rating for depth to water table. Each sufficiency rating is a normalized value ranging from 0.0 to 1.0. A sufficiency rating of 0.0 represents an absolutely limiting level of a soil or site property, while a rating of 1.0 represents the optimum non-limiting level of a property. The number of horizons within maximum rooting depth is represented by r. The weighting factor (WF) for each horizon varies by species; it is the optimum vertical proportion of roots in a horizon and is based on the thickness of each horizon. Optimum cumulative vertical root distributions (Y) to a depth (d) were estimated using a model developed by Gale and Grigal (1987),

$$Y = 1-\beta^d. \qquad (2)$$

The coefficient β is based on the tolerance rating or successional status of a tree species (Gale and Grigal 1987). Red pine, aspen, and jack pine were considered intolerant species (β=0.98) while red maple was considered

a midtolerant species (β=0.96). If all sufficiency ratings are 1.0, PI summed over all horizons will equal 1.0. If the sufficiency rating for any one factor within a horizon is 0.0, the PI for that horizon will also equal 0.0. Values of PI range from 0.0 to 1.0 with the latter value indicating a site of high productivity.

To determine species-specific sufficiency ratings for potential available water and pH for use in equation (1), normalized response curves were developed using information from previous studies. Common sufficiency ratings were developed for bulk density, climate, percent slope, and depth to water table and were used for all species. Some of the datasets did not contain sufficient information to use all of the sufficiency curves in equation (1). Bulk density information was missing for the aspen dataset, and percent slope, depth to water table, and plot locations (climate) were missing for the jack pine dataset. Sufficiency curves for these properties were not used in equation (1) to calculate PI for the respective datasets.

SOIL SUFFICIENCY CURVES

Sufficiency curves for potential available water (PAWC) (cm/cm) for each species were based on Stone et al.'s (1962) optimum PAWC for aboveground growth (Figure 1A). PAWC was adjusted for volume of stones greater than 2mm. Linear relationships were assumed between PAWC values of 0.0 to optimum PAWC,

$$\text{SUITAVW} = \text{PAWC} / \text{Optimum PAWC}, \qquad (3)$$

and a curvilinear relationship from optimum PAWC to 50 cm/cm,

$$\text{SUITAVW} = \text{Optimum PAWC} / \text{PAWC} \text{ (Gale 1987)}. \qquad (4)$$

These curve forms were used because of their simplicity and on the premise that a PAWC of 0.50 cm/cm or 50 % of soil volume limited root growth patterns by 50 %. Sufficiency curves for bulk density were taken from Pierce et al. (1984) (Figure 1B, three textural classes are shown, Gale 1987). Sufficiency curves for pH for each species were developed using optimum pH for each species cited by Spurway (1941) and Stone et al. (1962) (Figure 1C). Since pH's lower than 3.0 and higher than 8.0 are not common on forested sites, the sufficiency rating for pH at these values was set to 0.50 and a linear relationship was assumed between these and optimum values.

SITE SUFFICIENCY CURVES

The climate sufficiency curve was developed using an index of aridity (IA) proposed by Vysockiy (1905, cited by Czarnowski 1964). The index was calculated by dividing total precipitation by total evaporation for homoclimatic regions as tabulated by Rauscher (1984) (Figure 1D, Gale 1987). The sufficiency curve for percent slope was developed by Gale (1987) for white spruce (Figure 1E). This curve describes a decrease in productivity on slopes greater than or less than 15%. The sufficiency curve for depth to water table was developed from work by Stoeckeler (1960) (Figure 1F).

RESULTS

The PI explained 80 percent of the variation in site index for the aspen dataset but only 55 percent of the variation in site index for the jack pine dataset. Less than 16 percent of the variation in site index for the

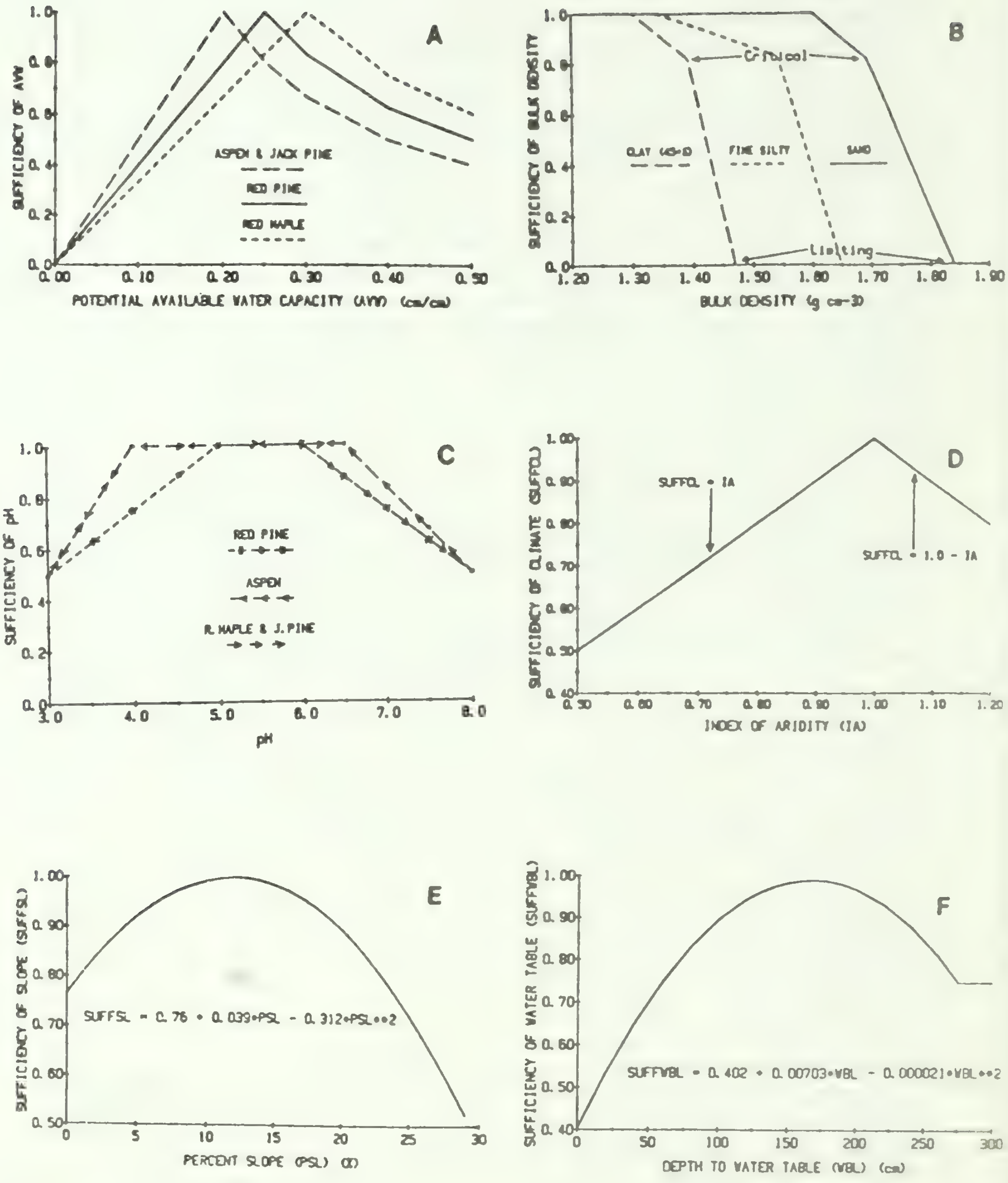

Figure 1: Sufficiency curves for A) potential available water capacity, B) bulk density, C) pH, D) climate, E) percent slope, and F) depth to water table.

red pine (r^2=0.06) and red maple (r^2=0.15) datasets was explained by PI. Poor results for the red pine and red maple datasets may be due to the large number of stands over age 50. The PI model may be a better predictor of site quality for younger stands than older stands because of the shift in importance from nutrients in mineral soil to those in organic horizons with stand maturity (Gale, 1987). Poor results may also be due to inaccurate sufficiency curves for those species.

Site index was significantly correlated ($p < 0.05$) with volume/biomass and mean annual increment for all datasets except for red pine volume (Table 1). For datasets with tree volume measurements (i.e., red pine, trembling aspen, jack pine), PI was significantly correlated with volume and mean annual increment. For the red maple dataset, PI was not significantly ($p > 0.05$) correlated with biomass measurements. Poor results for this dataset may be related to its average age or mixed species composition. The highest correlations between PI and stand production were for the aspen and jack pine datasets (Table 1). Site index was more closely related to volume/biomass and mean annual increment than was PI, except in the cases of red pine volume and jack pine mean annual increment (Table 1).

The addition of PI was compared to the addition of site index (SI) when used in a Schumacher-type equation (Schumacher 1939) (Table 2). In all cases, equations with site index explained more of the variation in stand production than did equations with PI (Table 2). Comparable results were observed for the red pine and jack pine datasets (Table 2). Better results for PI for the aspen and jack pine datasets (Table 1 and 2) may be due to the fact that each soil horizon was sampled in those data while in the other datasets either composite soil properties by soil depth (red pine) or estimates of missing observations for specific horizons (red maple) were used. Precision in PI may be lost when soil horizons are composited since each individual horizon is important to a tree's proportional rooting pattern and computation of PI. Imprecision in the development of sufficiency curves may have also produced poor results.

SUMMARY AND CONCLUSIONS

The PI model integrates the genetic rooting potential of a tree and its response to varying soil, climatic, and topographic conditions. It is not a regionally-specific model and can be used to predict site productivity on both nonforested and forested sites. The model may be improved by including sufficiency ratings for other soil/site factors such as soil nitrogen, soil phosphorus, soil organic matter, air temperature and competition. Development of species-specific sufficiency curves for climate and depth to water table versus curves common to all species as we have done in this study, may also improve the model. Additional testing of the model is needed to determine if the "optimum" soil and site sufficiency curves we have developed are accurate and if inaccurate calculations of PI occur with the use of composited soil characteristics.

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Table 1: Correlation coefficients (r) for volume, biomass, and mean annual increment (MAI) versus age, site index (SI), and productivity index (PI) for red pine, trembling aspen, jack pine, and red maple datasets.

RED PINE (63 plots)

	Volume (ft^3 ac^{-1})	MAI (ft^3 ac^{-1} yr^{-1})
AGE	0.36**	-0.40**
SI	0.05 .10	0.49**
PI	0.27*	0.33**

TREMBLING ASPEN (15 plots)

	Volume (ft^3 ac^{-1})	MAI (ft^3 ac^{-1} yr^{-1})
AGE	0.81**	0.49.10
SI	0.92**	0.93**
PI	0.87**	0.84**

JACK PINE (17 plots)

	Volume (cds ac^{-1})	MAI (cds ac^{-1} yr^{-1})
AGE	0.27NS	-0.35NS
SI	0.59*	0.66**
PI	0.53*	0.70**

RED MAPLE (37 plots)

	Biomass (t ha^{-1})	MAI (t ha^{-1} yr^{-1})
AGE	0.51**	-0.40*
SI	0.49**	0.83**
PI	0.16NS	0.24*

.10, significant at p=0.10 level ($0.05 < p < 0.10$)
*, significant at p=0.05 level ($0.01 < p < 0.05$)
**, significant at p=0.01 level ($p < 0.01$)
NS, not significant at p=0.10 level ($p > 0.10$)

Table 2: Comparison of multiple curvilinear regression equations to predict stand volume (VOL), biomass (STB), or mean annual increment (MAIV, MAIB) with age using productivity index (PI) versus site index (SI) for red pine, trembling aspen, jack pine, and red maple.

RED PINE (63 plots)

Equation	R^2	Sy.xx[1]
LNVOL = 8.09 - 31.6 (1/AGE) + 1.51 (PI)	0.24**	0.21
LNVOL = 8.31 - 48.8 (1/AGE) + 0.02 (SI)	0.24**	0.21
LNMAIV = 2.99 + 28.5 (1/AGE) + 1.46 (PI)	0.24**	0.20
LNMAIV = 3.21 + 12.0 (1/AGE) + 0.02 (SI)	0.25**	0.20

TREMBLING ASPEN (15 plots)

Equation	R^2	Sy.xx
LNVOL = 4.58 - 25.6 (1/AGE) + 5.00 (PI)	0.83**	0.20
LNVOL = 5.79 - 17.7 (1/AGE) + 0.03 (SI)	0.95**	0.12
LNMAIV = 0.12 + 8.2 (1/AGE) + 4.90 (PI)	0.69**	0.20
LNMAIV = 1.27 + 16.4 (1/AGE) + 0.03 (SI)	0.92**	0.10

JACK PINE (17 plots)

Equation	R^2	Sy.xx
LNVOL = -3.03 - 29.0 (1/AGE) + 8.87 (PI)	0.36*	0.31
LNVOL = 2.61 - 24.6 (1/AGE) + 0.02 (SI)	0.42*	0.30
LNMAIV = -7.70 + 17.9 (1/AGE) + 8.61 (PI)	0.43*	0.30
LNMAIV = -2.19 + 22.5 (1/AGE) + 0.02 (SI)	0.47*	0.29

RED MAPLE (37 plots)

Equation	R^2	Sy.xx
LNSTB = 5.40 - 37.4 (1/AGE) + 0.89 (PI)	0.31**	0.20
LNSTB = 4.72 - 51.1 (1/AGE) + 0.08 (SI)	0.73**	0.12
LNMAIB = 0.24 + 21.3 (1/AGE) + 1.02 (PI)	0.18*	0.20
LNMAIB = -0.40 + 7.3 (1/AGE) + 0.08 (SI)	0.68**	0.12

1, Standard error of multiple regression
*, significant at p=0.05 level ($0.01 < p < 0.05$)
**, significant at p=0.01 level ($p < 0.01$)

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CONSTRUCTING SITE SPECIFIC HEIGHT GROWTH CURVES

Kelsey S. Milner[1]

ABSTRACT. In this study, Zeide's (1978) two-point system for approximating height growth curves was used to investigate sources of variation in height growth patterns, and to build site specific height growth curves for Douglas-fir in western Montana. Results showed that: (1) the Zeide two-point system is an accurate method of approximating height growth curves, provided appropriate observations are used; (2) the index of curve shape, Z, is a useful attribute in assessments of the applicability of published site curves to local populations; (3) for the data, shape of the height growth curve was not correlated with site index, but was with soil and climatological variables; (4) a system for estimating height growth curves based on Zeide's two-point system has the potential to be more accurate, on a site specific basis, than the traditional site index system.

INTRODUCTION

In many yield prediction systems, a potential height growth curve is used as the "driver" of the basic growth functions. Accurate site specific predictions of future yield, therefore, depend on specification of the appropriate potential curve for a given site. Commonly, the potential curve for a site is obtained from a set of site curves.

Numerous studies have demonstrated that the relationship between height growth and site index changes from region to region in response to soil and climatological factors (Carmean, 1956; Hoyer and Chawes, 1980; Monserud, 1984). There may be a substantial amount of variation in the shape of potential height growth curves, even within relatively small regions, that could be accounted for by methodologies that do not assume a single curve shape for a given level of site index. The curves by Monserud (1984), which account for differences in curve shape between habitat type series confirms that this is the case.

This paper reports on research done in western Montana on the sources of variation in height growth patterns for inland Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco var. *glouca*). Two objectives were: (1) to investigate sources of variation in the height growth patterns of dominant trees, and (2) to explore alternatives to the traditional site curve method of obtaining a potential height growth curve for a specific site.

METHODS

DATA COLLECTION

Data for the study were gathered in western Montana on state, federal, and private land representing most of the major landowners in the

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region. The area has two major climatic regions each of which exhibits a complex mosaic of glacial, alluvial, volcanic, and colluvial processes. Observations of height growth patterns were obtained via stem analysis of "site" trees from sites stratified by elevation, precipitation, and aspect. At each site the tree of median measured site index, from a sample of three trees, was sectioned.

At each site, values for a variety of soil and climatological variables were formed. These included soil water holding capacity, soil texture and depth, monthly precipitation, monthly daylight temperatures, and monthly solar insolation loads. Details of how these values were obtained are contained in Milner (1986).

ANALYSES

The stem analysis data were used to construct a set of site curves for the study area. The procedures followed those described by Curtis, et. al. (1974), and later by Barrett (1978). The method produces polymorphic curves with respect to site index.

Zeide's (1978) two-point system for describing height growth curves was tested as a suitable method of characterizing the height growth pattern of dominant trees. The Zeide two-point system is described in Zeide (1978), Hoyer and Chawes (1980), and Arney (1984). Briefly, the system is a method of estimating growth trajectories from two sequential observations of height and age. From the two observations, a growth curve type, or Z number, is determined that references a unique relative growth curve that Zeide developed from samples of real growth series. Given the Z number and one of the observations of height and age, a complete growth series can be produced. An analysis of height residuals (observed-predicted) was used to identify those pairs of observations that generated similar height growth curves. A computerized version of Zeide's tabular system (Arney 1984), was used to determine the Z numbers and the corresponding height growth curves for each set of observations.

The Z numbers were used as the dependent variable in analyses designed to investigate sources of variation in curve shape. Independent variables included site index, and various single and two-way interaction terms formed from the soil and climatological measurements. A comparison was made between the precision of a system using the Z numbers, both measured and predicted by soil/site variables, and the traditional site curve system built from the data.

RESULTS

SUITABILITY OF THE ZEIDE TWO POINT SYSTEM

Figures 1a-1d show plots of height residuals (observed minus predicted), for several combinations of height and age pairs taken from the height/age data. Observations from early in the growth series that are separated by only a few years produce a scatter of residuals which indicates that the system is unstable (Fig. 1a). Similar instability is seen from the scatter of residuals for observations taken close together late in the growth series (Fig. 1b). This imprecision is not unexpected since the curves are based on raw data points which from year to year naturally deviate from the long-term average trend. Minor deviations at

one end of the growth curve will be magnified at the other end. An observation at an extreme age may be used so long as the paired observation is at least 40 years removed (Fig. 1c). Observations within the middle third of the growth series may be separated by as little as 20 years (Fig. 1d).

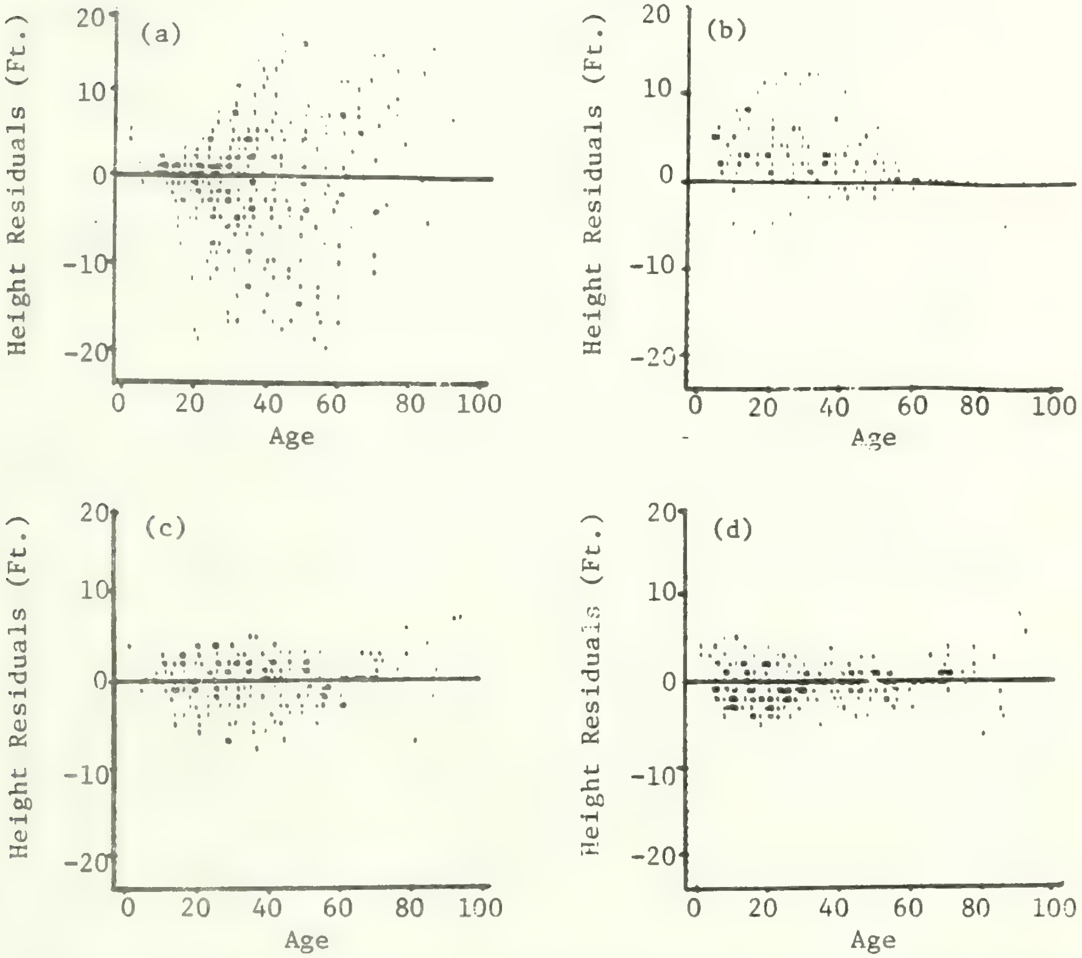

Figure 1. Height residuals (observed-predicted) for Zeide's two-point system. Ages at which heights are taken are: (a) 0, 10; (b) 60, 70; (c) 0, 40; (d) 30, 50.

Thus there is considerable latitude in the choice of height/age pairs that can be used in the Zeide system. Arney's (1984) recommendation of observations at 30 and 60 years gave consistent results and was used as the standard for this study.

VARIATION IN SHAPE OF THE HEIGHT GROWTH CURVE

Figure 2 shows the scatter of Z values vs. site index for the data. Recall that only one tree per site was sectioned so that the variation displayed contains both tree-to-tree and site-to-site sources of variation. An estimate of within site variation in Z number was obtained from three plots where from three to six trees were sectioned.

This was used together with the estimate of total variation to estimate between site variation. It was estimated that roughly 80% of the variation shown in Figure 2 is due to differences between sites.

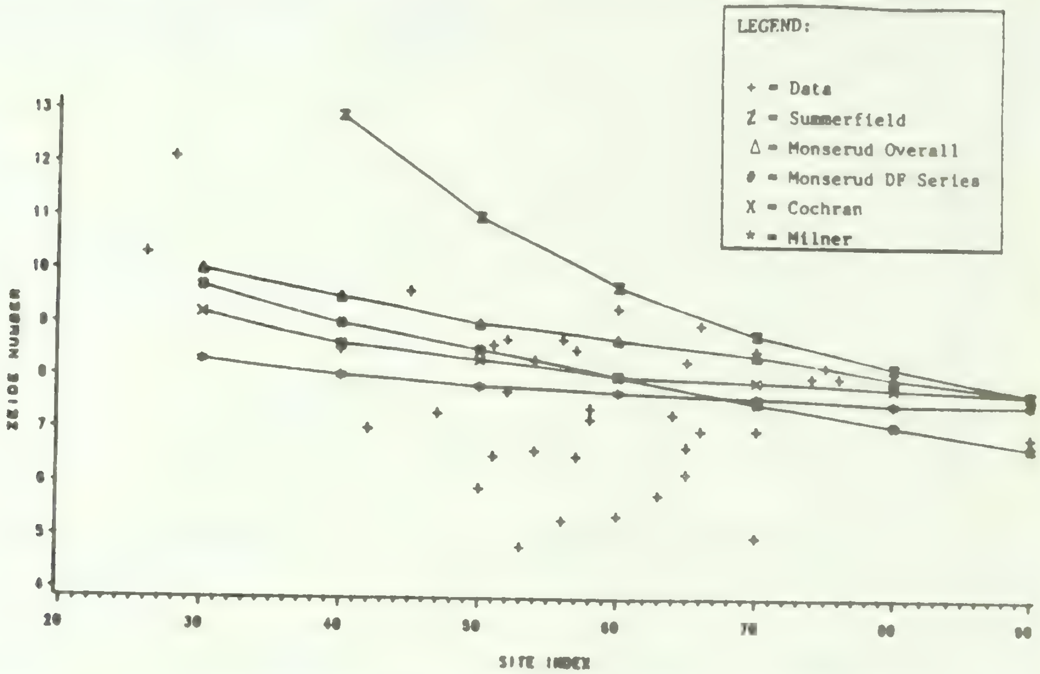

Figure 2. Curve shape index, Z, vs. site index for data and several published height growth curves for Douglas-fir.

The value in being able to account for some of this variation in curve shape is suggested by the yield curves shown in Figure 3. The graphs display the total cubic volume yield predicted for a site index 60' using the average Z number and the Z value at plus and minus one standard deviations. Assuming for the moment that the growth model predictions are truth, the yield curves suggest that differences in Z number of one or two units are of practical importance.

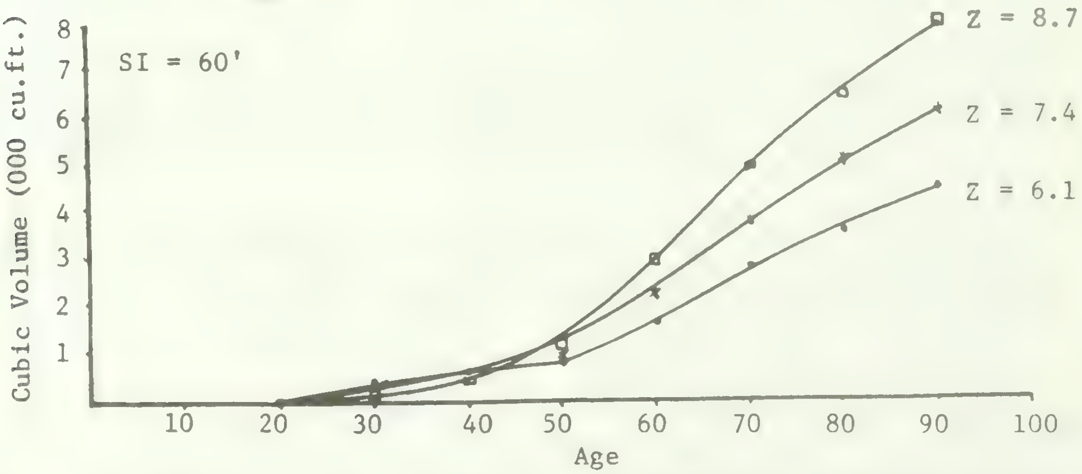

Figure 3. Total cubic volume vs. age for three values of Z, within a site index = 60'. Z values are the mean and ±1 SD.

The data in Figure 2 show that there is little or no trend in the curve shape index Z, with respect to site index. The plot of Z values computed for the height growth curves derived from the data reflect this lack of polymorphism. If a substantial amount of the variation displayed in Figure 2 can be explained by site factors, then there should be opportunity to significantly improve our estimations of site specific height growth curves. Monserud's (1984) site curve system is an example of one way to do this. Habitat type effects are represented through use of dummy variables that affect the influence of site index on the height/age relationship. The differences between the overall height growth equation and that for the Douglas-fir habitat types is easily seen in Figure 2.

As an analytic tool, the display of Z values as in Figure 2 allows a rapid evaluation of site curve validity for the population of interest, and permits ready comparison of multiple sets of curves. For example, overlayed on the plot of the data are the Z values calculated for several site curve systems in use in the study area. In contrast to the data, Summerfield's curves generated high Z values and showed a marked trend with site index. High Z values mean that the curves will underpredict at young ages (for a given site index), and overpredict at older ages. For Summerfield's curves, this bias will be greater on low sites than on high sites. An advantage of this sort of display is that differences in height growth pattern can be examined across levels of site index. This is not easily done with the standard presentation of residuals.

PREDICTION EQUATIONS FOR ZEIDE GROWTH CURVE TYPES

An effort was made to build prediction equations for the growth curve type Z using site and climatological variables. Table 1 summarizes the results of the effort for Douglas-fir for the data on plots with slopes of greater than 10%. For the data from slopes less than 10%, means by habitat type were more precise. Generally, plots of the data showed little or no trends with single factors. The only significant, single factor was afternoon solar radiation, which was inversely related to Z. However, a measure of soil texture, % silt in the profile, entered consistently as part of two-way interaction terms with solar radiation, precipitation, and temperature. Interpretation of the coefficients of the final regression equations is dangerous given the small sample size, the somewhat "kitchen sink" modeling approach, and the non orthogonality of the independent variables. The equations are "best fit" models and may or may not extrapolate to combinations of the independent variables not included in the data.

Table 1. Z prediction equations for Douglas-fir.

Variable Set	Equation	Statistics R^2	RMSQ
SI	NS	---	----
SITE	Z = 10.73 - .00000031 AS*T	.28	1.19
SITE + SOIL	Z = 6.36 - .00033 AS*S - 553.3 T/AS + 1.56 S*P + 5931/(P*T)	.54	1.05

where: SI = site index, P = total precipitation for March through June, T = sum of average daytime temperature for March through June, S = % silt in top 3' of profile, AS = cummulative afternoon solar radiation for March through June.

COMPARISON OF THE ZEIDE BASED AND TRADITIONAL SITE INDEX SYSTEMS

A Zeide based system for estimating a potential height growth curve for a site would involve first predicting a Z number from site characteristics, or obtaining a value from measurements of height and age. The second step would be to supply a height and age pair that reflected site potential for height growth. The resulting height growth curve should be closer to the actual curve than one obtained by the traditional site curve system that uses an average curve shape.

Table 2 shows a comparison of the precision with which the two systems predict height at various ages, for several ages of "site" trees.

When the Z number is predicted and very young site trees are used, the site index system is consistently more precise than the Zeide system. For older trees using predicted Z values, the two systems exhibit similar precision. When the computed Z value for each tree is used, the Zeide system is more precise. For both systems, precision increases as the site trees get older. Clearly, there is little information about future height growth contained in ten-year-old trees.

There are at least two reasons why the Zeide system did not show the anticipated increase in precision when using the predicted Z values. First, the error term associated with the regression equations is still fairly large, compared to the standard deviation of the sample mean (root mean square error of regression=1.1; sample standard error=1.3). Thus, the equations do not provide for a major increase in precision in estimating Z numbers, over using the sample mean. Second, with the site index system, the use of a site index equation tends to dampen the effects of deviations in height from the long-term trend. The greater tendency of the Zeide system to magnify effects of deviations about long-term trends is sufficient to mask the relatively small gains made in the estimation of curve shape by the prediction equations. A more stable estimate of site height would improve the performance of the Zeide system.

Table 2. Comparison of accuracy (R) and precision (SD_R) with which the Zeide and site index systems estimate height growth patterns, for three levels of tree age, for Douglas-fir.

Entry Age	Age	Predicted Zeide No. $\bar{R}$	Predicted Zeide No. SD_R	Predicted Zeide No. $SE_{\bar{R}}$	Actual Zeide No. $\bar{R}$	Actual Zeide No. SD_R	Actual Zeide No. $SE_{\bar{R}}$	Site Index $\bar{R}$	Site Index SD_R	Site Index $SE_{\bar{R}}$
		Feet								
10	10	0.000	0.00	0.00	0.00	0.00	0.000	-1.80	1.14	.17
	20	-.260	3.15	.47	-.44	3.74	.550	.32	2.92	.43
	30	.100	6.45	.96	-3.90	7.80	1.160	1.32	4.90	.72
	40	.010	9.01	1.34	-.83	10.47	1.560	1.69	6.24	.92
	50	-.200	11.48	1.71	-1.39	12.48	1.860	1.52	7.74	1.14
	60	-.670	14.10	2.35	-4.11	14.72	2.450	.43	9.50	1.58
	70	-.890	16.48	3.17	-8.41	17.26	3.320	.36	11.67	2.24
	80	-5.460	14.94	4.31	-8.86	18.29	5.280	-.80	12.52	3.62
30	10	-.170	1.98	.29	-.16	2.26	.340	-.58	1.57	.23
	20	-.420	1.70	.25	-.41	1.80	.270	-.54	1.49	.22
	30	0.000	0.00	0.00	0.00	0.00	0.000	.03	.57	.08
	40	-.002	2.24	.33	-.02	1.38	.210	.02	2.24	.33
	50	-.090	4.04	.60	-.15	1.23	.180	-.47	3.97	.58
	60	.880	5.45	.91	-.01	.02	.004	-.31	5.37	.89
	70	2.890	6.43	1.23	.47	1.67	.320	1.06	6.60	1.27
	80	1.590	4.21	1.21	.82	4.08	1.180	-.07	8.15	2.35
70	10	-.140	2.63	.51	.76	2.20	.420	-.51	2.25	.43
	20	-1.230	3.75	.72	.07	1.87	.360	-1.02	3.24	.62
	30	-1.570	3.53	.68	-.27	.85	.160	-.83	3.45	.66
	40	-1.590	3.23	.62	-.50	1.86	.360	-.62	3.18	.61
	50	-1.320	2.18	.42	-.56	1.98	.380	-.47	2.40	.46
	60	-.840	1.50	.29	-.47	1.50	.290	-.40	1.58	.30
	70	0.000	0.00	0.00	0.00	0.00	0.000	-.21	.83	.16
	80	.440	1.73	.50	.39	2.24	.650	-.42	1.73	.50

CONCLUSIONS

The results of this study have shown that accurate estimates of potential height growth curves can be developed using the Zeide two-point system. The two observations of height and age can be from a variety of points on the tree, with the time interval between them depending on how close one point is to an extreme. In particular, acceptable results were seen for pairs where the first point was at less than 10 years breast high age, provided the second was at least 40 years of age. This suggests that for trees more than 40 years old, current height and age, and height and age for a point within reach of an observer would be sufficient.

The Z values are also useful in exploring sources of variation in curve shape. Rather than having to examine change in several regression parameters in response to environmental gradients, a single variable is sufficient. Zeide numbers are also useful for evaluating the validity of a particular site curve system for use in a particular area, and for comparing several sets of curves simultaneously. It would take many displays of residuals to convey the same information that can be contained in a single plot of Z values vs. site index.

In this study, it was clear that while there was substantial variation in curve shape, it was not correlated with site index. Thus the traditional site curve system constructed from the data contains a single curve shape that is applied to all sites. Based on growth model predictions, estimates of yields for specific sites could be greatly improved with a system that captured some of this variation. If Zeide numbers for site can be developed from observations of height and age, then gains in precision can be made in the estimation of site specific yields relative to that for the site index system. If tree-based estimates of the Z number are not feasible, it is possible to predict them from soil and climatological variables. However, more precise Z prediction methods and/or more stable estimates of site height are necessary.

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VARIATIONS ON A THEME OF SITE INDEX

Robert A. Monserud [1]

ABSTRACT. Several aspects of site index are explored. After a brief historic overview, numerous problems are discussed that result from the application of site index in irregular stands with a mixed species composition and an uneven distribution of ages. Although careful site tree selection can overcome some of these problems, the solution to others remains a mystery. An examination of environmental and genetic factors associated with site index variation in Douglas-fir revealed that elevation and habitat type were jointly the best predictors of site index, that soil characteristics accounted for little of the variation, and that a simple genetic index (3-yr seedling height in provenance tests) explained more site index variation than the best set of environmental factors.

SITE INDEX OVERVIEW AND HISTORICAL PERSPECTIVE

Site index (the height of dominants at an index age) is by far the most common measure of productivity in North America (Spurr and Barnes 1980). Site index is popular because it is relatively easy to measure and dominant height growth is fairly independent of stand density (except at the extremes). Also, there is strong historical precedent for its use.

Early in the 20th century the practice of forestry was almost nonexistent in this country. The newly created Forest Service was at a considerable disadvantage pursuing its goal to achieve First Chief Gifford Pinchot's ideal of wise management, for neither yield tables nor a measure of the productivity of the forest resource were available. From 1910 to 1923 a debate raged regarding the method of measuring productivity to be adopted by the profession (see Mader 1963, Monserud 1984b). Frothingham (1918, 1921) and Roth (1916) advocated height growth (i.e., site index), Bates (1918) pushed for volume growth, and Zon (1913) championed Cajander's vegetative site types. After much discussion the Society of American Foresters (1923) ruled that site index was the winner. Shortly thereafter Bruce (1926) issued his guidelines on constructing normal yield tables. They were based on temporary plots (remeasured permanent plots did not exist). Stem analysis was eschewed, for Bruce did not believe individual tree growth could be used to index stand development. Proportional guide curve methodology was the basis of the tables, which were entered via site index and age.

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Although these guidelines were essentially an exercise in expediency, they became the basis for almost all the yield tables that were developed until about 1960. The strange thing is that site index was never directly observed when the yield tables were built (unless the stand was at index age). It was only inferred from the guide curve, a mere mental construct rather than the real height growth curve that foresters thought they were indexing. And this mental construct took on a life of its own.

The methodology underpinning the guide curve pivoted on one crucial assumption, an assumption that is almost never true: that site index was uniformly sampled for every age class (Spurr 1952). Only when this is true will the guide curve actually follow the average growth curve. Monserud (1985a) recently conducted a controlled experiment to measure the magnitude of the bias that can result from Bruce's guide curve methodology. Observed site index in Monserud's sample declined from a height of 66 ft at age 50 down to a height of 55 ft at age 200, which invalidates the uniform site-age assumption. This decline resulted in a height growth bias of more than 40 ft at age 200 when guide curve methods were used (Figure 1). In spite of the potential for such large biases, the site index curves used to enter the yield tables were never critically examined until mid-century. Even in the 1980's examples of this flawed methodology can be found in the literature (citations withheld to protect the guilty).

By the 1950's the normal yield tables had been in use long enough for deficiencies to become apparent. The most common shortcoming was that too many factors were ignored or that the tables were too broadly designed and applied. Barnes (1949) found large differences between the height growth pattern of sitka spruce and western hemlock, even though both species were combined in the same yield table. Carmean (1956) found that the coastal Douglas-fir curves were biased for both excessively and imperfectly drained soils. Daubenmire (1961) found large biases that resulted from ignoring habitat type differences in the ponderosa pine site curves. And Spurr (1952) and later Curtis (1966) both found significant differences greater than 20 ft between permanent plot growth and predictions from the Douglas-fir site curves. The result of these and similar criticisms was that by 1960 the guide curve methodology was largely abandoned in favor of stem analysis, where site index could actually be observed. In addition, because the actual pattern of height growth was also observed, any polymorphic growth patterns that were found could now be modeled in a straightforward manner. There was no longer any need to assume that the shapes of the height growth curves were the same (i.e., proportional) regardless of site index.

PROBLEMS IN IRREGULAR STANDS

That the concept of site index is quite useful is without doubt--otherwise it would never have remained the most popular index of forest productivity for all of this century. To point out the advantages of site index would be both obvious and pedantic. Instead, I am going to discuss some problems with the application of site index, specifically in the northern Rocky Mountains.

These forests are mesic, mountainous, and vast. More often than not, stands are quite irregular both in age structure and species composition. It is uncommon for a stand to contain less than three of the dozen commercial species. Pure even-aged stands do occur, of course, both as a result of clearcutting and wildfire. But even though a stand may start out as pure and even-aged, it often does not end up that way. With a number of tolerant species capable of slowly invading plantations, it is almost naive to assume that most stands will satisfy the classic even-aged single species assumptions that are the cornerstone of most site index systems.

After charging site index windmills in such irregular forests, several problems soon become apparent:

• Too many species are present. Species composition is often mixed and unpredictable. It is difficult to determine which species will be the best indicator of site productivity.

• No site curves are available for many species. In the northern Rockies, site curves simply do not exist for the most tolerant species (western redcedar--the region's most expensive species--as well as western hemlock and subalpine fir).

• Stand age may be meaningless. This is obviously true in the numerous uneven-aged stands found in the region.

• Tree age may be unobtainable. Heart rot is a common problem in several species (western redcedar, western hemlock, grand fir), especially in the old-growth trees that would likely be chosen as potential site trees. An additional problem may be the sheer size of some of these trees. They may be too large for the largest available increment borer to reach the pith.

• Dominant trees may have survived suppression. It is not wise to assume that the tallest or largest trees will give the best indication of potential growth.

• Potential site trees may have survived a growth-reducing pest attack. The region has a long history of insect and disease problems. Clearly an unknown past outbreak of defoliators such as tussock moth or spruce budworm could bias the estimate of site index.

Monserud (1984a, 1985b) demonstrated that several of these problems can be overcome through careful selection of site trees. This involves examination of increment cores to make sure that the trees are indeed indicative of the potential of the site to grow wood. Even with careful site tree selection, several of the preceding problems with site index cannot be overcome in many irregular stands.

Given this myriad of problems, it should come as no surprise that Stage (1973) and later Wykoff and others (1982) intentionally ignored both site index and age as predictor variables in developing their Stand Prognosis Model for the forests of northern Idaho and western Montana.

Considering the broad scope of Prognosis (it is designed to provide long-term growth projections for any stand that appears on any inventory in the northern Rocky Mountains), variables that were not consistently reliable simply had no business influencing the projections. Obviously, some measure of site productivity was needed to replace site index (and age). The current models (primarily basal area increment) use habitat type, slope, aspect, elevation, and geographic location as aliases for site productivity. Further localization is achieved by using past diameter increment data to adjust the basal area increment model (this is termed calibration). The fact that the Prognosis Model is one of the most widely used growth and yield models should provide considerable encouragement to those working on modeling stand dynamics in irregular forests. As Wykoff and Monserud (1987) have demonstrated, site index and age are not necessary to produce good growth predictions.

ENVIRONMENTAL AND GENETIC FACTORS INFLUENCING DOUGLAS-FIR SITE INDEX

When I moved to Idaho I was curious to do some research on site index, especially after realizing that Al Stage didn't use his own grand fir site curves in the Prognosis Model. I picked Douglas-fir to work on because not only is it the most common and important species in the Rocky Mountains, but it also has a wide ecological amplitude. Although site curves had been derived for Douglas-fir using guide curve methods, it was obvious to me that they were quite likely biased, especially past index age (see Monserud 1985a for discussion). Thus, stem analysis procedures were called for.

In addition, the prevalence of irregular forests in northern Idaho strongly influenced the way I conducted my site index study. Because I wanted the results to be generally applicable, I eliminated all constraints on age structure and species composition. Any stand with suitable Douglas-fir site trees was acceptable. This necessitated examining increment cores from all potential site trees before choosing the trees that best indicated the sites' productivity. Although this required more work than normal for site tree selection, it solved the problem that the largest trees in an irregular stand may have survived suppression or damage. After surviving at least two independent validation studies, it appears that the resulting curves (Monserud 1984a, 1985b) seem to describe dominant height growth well. One unusual result was that the shape of the height growth curves changed with the climax vegetation (Figure 2). Height growth drops off significantly on the dry Douglas-fir climax stands and it continues much longer than average on the mesic western hemlock and subalpine fir climax stands.

Because good site trees are not always available for estimating site index, I was also curious to see how well a broad range of environmental variables could predict site index. Even though habitat type explained a significant amount of variation in the shape of the curves, it was a fairly poor predictor of the actual level of site index (R^2 = .21). Elevation was more important, explaining almost a third of the variation. The combination of elevation and habitat type

explained 39 percent of the variation. The addition of longitude explained a few more percentage points. Other topographic descriptors (such as slope, aspect, and latitude) were not significant.

With the strong expectation that soil characteristics would explain an important amount of variation in site index, I arranged for soil scientists to sample all study plots. The standard list of soil characteristics were measured, including both chemical and physical properties. Results were extremely disappointing, for no combination of soil variables accounted for anywhere near the same amount of variation as elevation and habitat type. The best soil model only explained 16 percent of the variation in site index. Monserud et al. (1986) speculated that a likely explanation for such low soil-site correlations is that the standard soil sampling procedures fail to measure the true causes of site productivity. Obviously, soil is important to tree growth. Perhaps it is equally obvious that we don't really understand how to measure most of the soil processes that relate directly to site productivity.

Just as all forest growth modelers realize that soil and climate are major factors influencing tree growth, they also realize the importance of genotype. Quantifying this genetic effect is rarely attempted, however, especially by mensurationists. Because of a fortuitous collaboration in the spring of 1987, I was able to incorporate the results of Rehfeldt's (1987) genetics experiments into my Douglas-fir analysis. Based on provenance tests, Rehfeldt constructed a genetic index (3-year seedling height) using the elevation, latitude, and longitude of the seed source. The most surprising aspect of this study (Monserud and Rehfeldt 1987) was that this genetic index was by far the most significant predictor of site index ($R^2 = .42$). It alone was better than the best set of environmental predictors and far more important than any set of measured soil characteristics.

Because Monserud and Rehfeldt (1987) were primarily interested in isolating the independent contributions of genotype and environment on site index, a path analysis (Wright 1934) was conducted. Results indicated that the genetic makeup of Douglas-fir is about a third more important than environment in determining phenotypic variation in dominant height in natural stands. The correlation between genotype and environment was strong ($r = 0.76$), reflecting the steep adaptive clines that are well known for Douglas-fir. Rehfeldt (1987) speculated that his genetic model is most likely indexing (or aliasing for) frost-free period, which appears to be the underlying source of the genetic pressure.

Just what are the implications of this analysis as far as growth modelers are concerned? I find it amazing that genetic index--a variable that none of us uses--explains more variation in height growth than any of the available environmental descriptors. With the sole exception of western white pine in the Northwest, it appears untenable to assume that the genetic structure of our modeling substrate is constant. Clearly, a variable that requires at least a 3-year bioassay technique is not going to become popular in the modeling community. But for Douglas-fir, at least, local adaptation is so strong that

easily measured environmental variables (elevation, latitude, longitude) can be used to index the genotype. However, properly conducted genetics experiment is necessary to find the transformation that breaks out the underlying relationship.

I am both surprised and disappointed at the failure of the measured soil characteristics to explain an important amount of variation. Perhaps most of the variation is caused by climatic effects such as the temperature regime of a site (the significance of the genetic index points to this). My hunch is that within a seed zone (500 ft in elevation for Douglas-fir) soil might explain a significant portion of the remaining variation. However, there appears to be no generality across all seed zones and across the entire study area (25,000 mi^2).

SUMMARY

The utility of site index has been taken for granted in forestry. While this traditional attitude has largely been sound, there are nevertheless situations where it is unjustified. Serious methodological flaws in the logic of normal yield table construction resulted in the creation of a site index construct that was not based on a real growth curve; biased height versus age curves were the outcome. Stem analysis methods (or remeasured permanent plots) have largely solved these problems. Biological problems with site index can also arise, especially in irregular forests with mixed-species composition and an uneven distribution of ages. When applying the site index concept to such forests, care must be taken to ensure that the site trees are indeed indicative of the productivity of the site. This usually requires the detailed examination of increment cores before choosing site trees.

It is also assumed that commonly measured soil characteristics can easily be used to index site productivity. Results from my Douglas-fir site index study, however, indicate the contrary. The actual soil factors that relate directly to site index appear to be as inscrutable as they are difficult to measure.

An even more common assumption regarding site index is that the genetic substrate is constant. Results from Monserud and Rehfeldt (1987) indicate that this assumption is clearly untenable, to the extent that genotype explained more site index variation than environment. The implications for growth modelers are great. For example, more than half of the variation that would normally be ascribed to elevation is, in fact, a genetic trait of the Douglas-fir growing on the site. If we hope someday to elucidate the true causes of site productivity we cannot overlook the genetic structure of trees adapted to that environment.

In conclusion, the proper use of site index as a research tool requires close examination of all assumptions underlying the concept and all factors affecting its measured value. Site index obviously can be a useful management tool, but only if it is used wisely.

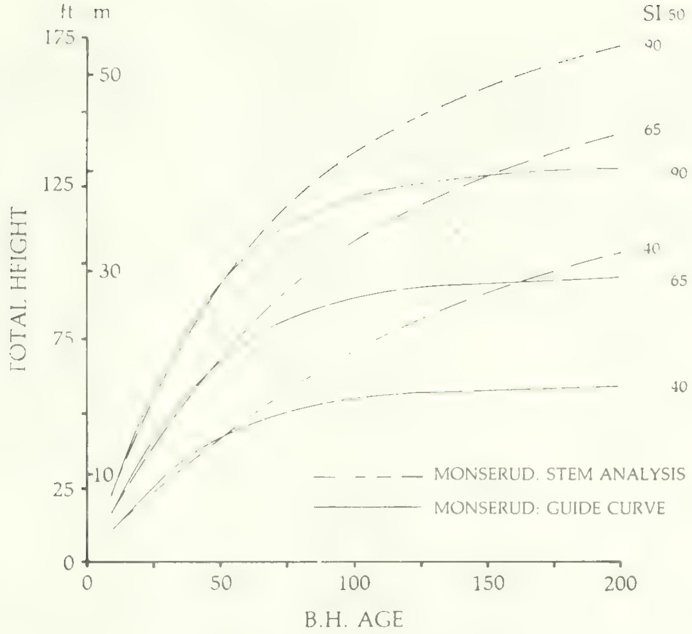

Figure 1. Comparison of Monserud's (1984a) stem analysis model with a proportional guide curve model fit to the same sample trees (from Monserud 1985a).

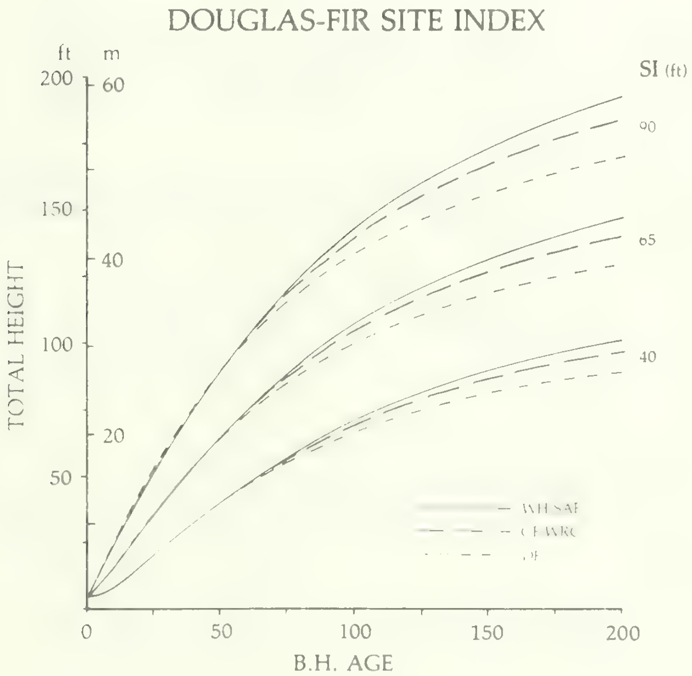

Figure 2. Inland Douglas-fir site index curves (Monserud 1984a) for each of the three habitat series groups (WH-SAF is western hemlock and subalpine fir climax, GF-WRC is grand fir and western redcedar climax, and DF is Douglas-fir climax), and for three site index levels (approximately the minimum (40), mean (65), and maximum (90) site index sampled).

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COMPARISONS OF SOUTHERN PINE HEIGHT GROWTH

Mike R. Strub and Peter T. Sprinz[1]

ABSTRACT. Common anamorphic and polymorphic sets of height versus age equations were found inadequate in describing the shape of this relationship. A piece wise linear growth equation proved satisfactory in defining the shape of height versus age trends. This model allows interpretation of parameters describing curvature during time intervals, and allows comparison of curve shapes with statistical tests. The four southern pines tested were found to have significantly different curve shapes between ages eleven to thirty-nine. No significant difference in shape was detected from ages two to eleven or thirty-nine to fifty-six.

INTRODUCTION

The purpose of this work is to develop methodology for determining differences between height versus age trends. Anamorphic systems of equations have different levels, but have the same shape. Polymorphic systems can assume different shapes as well as different levels. Although these systems may assume many different shapes they may not be flexible enough to detect important shape differences between classes of trees. The inadequacy of a popular anamorphic and a polymorphic system to detect these differences will be demonstrated. Methodology for detecting shape differences will be developed.

Data used in these comparisons are from four southern pines managed in a similar way at the same site. The same techniques can be used to compare different seed sources within a species, or families within a seed source. Such comparisons can indicate what level of modeling is necessary to manage different species, seed sources, and families. It has been suggested that at least at the family level, and perhaps at the seed source level that different classes may be modeled by merely changing the site index. The techniques developed here can be used to test the validity of this proposition.

THE DATA

The data for this study was collected at the Texas Forest Service Siecke Experimental Forest near Kirbyville, Texas. Large blocks of 6 x 6 foot spacings were planted with each of four southern pine species in 1930. The

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four pine species planted include shortleaf (Pinus echinata), longleaf (Pinus palustris), loblolly (Pinus taeda), and slash (Pinus elliottii) pines. Similar management techniques were applied to each of the blocks. The blocks were thinned several times and prescribed fire was used to control the underbrush. The block containing longleaf pines was devastated by pine bark beetles, so an adjacent one year younger block was used to collect information on this species. This adjacent plot was managed in a similar fashion. In March, 1986, five dominant trees in each species were felled for collection of stem analysis data. Upon close examination, one of the supposed slash pines was found to be a different species and was dropped from the study.

The stem analysis procedure included bucking trees into five foot bolts and splitting all sections that did not contain external evidence of branches. The age at the end of each bolt was determined by counting rings. The exact delineation of each year's growth was determined by studying branch positions from either internal evidence on split blots or external evidence where available. The length of each year's growth was determined in this way. The full fifty-six year's growth was not available on trees whose tops were broken and lost during the felling operation. The first few year's growth was not available in some cases as it was contained in the stump.

Final data for the study consisted of height, age and growth age pairs for fifty-six or fewer years on each nineteen trees. Height growth was paired with the initial age. For example, height growth between ages two and three was paired with age two. The average of the data by species is plotted in Figure 1. Figure 1 shows different shaped height versus age curves for each of the four species. This data was smoothed by averaging growth across all available trees and then summing growth to determine average height. This gives a smoother trend than just averaging heights since not all trees have height measurements at all ages.

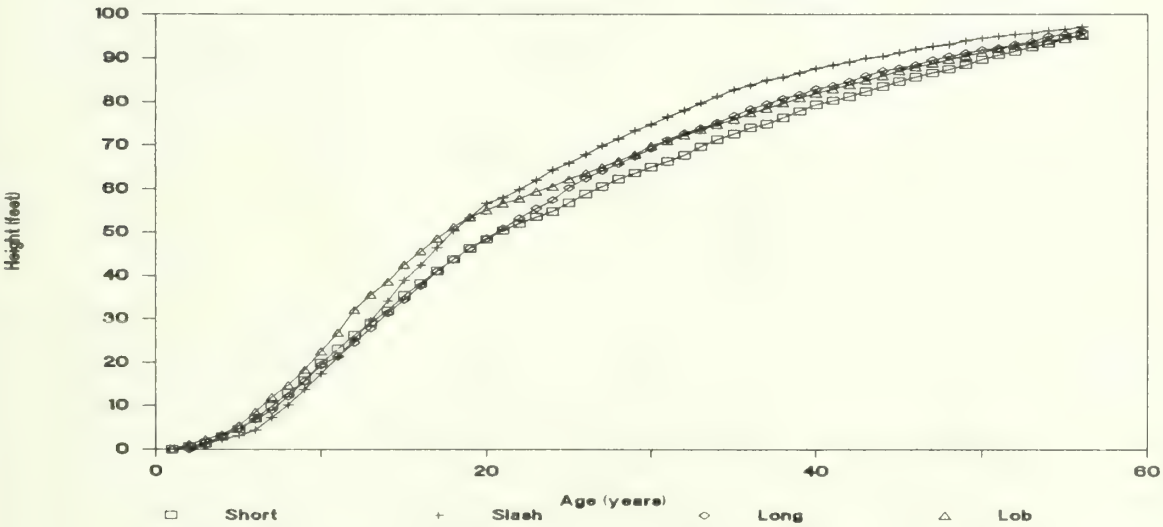

Figure 1. Observed height versus age trend for shortleaf, slash, longleaf and loblolly pine.

The different shapes of height versus age trends in Figure 1 indicate different growth strategies exhibited by each of the four species. Loblolly pine exhibits fast early growth and then reduced growth after the early teens. Slash pine exhibits slower initial growth with good growth through the late teens and the twenties surpassing loblolly pine in the mid-teens. Shortleaf pine shows slower initial growth but good growth late in life catching loblolly and slash pines by the early fifties. Longleaf pine also exhibits slow early growth and faster growth late in life. The development of an analytical technique for describing and testing the statistical significance of these different height versus age trends is the purpose of this study.

THE ANAMORPHIC MODEL

A typical anamorphic model is the logarithm of height versus inverse age. This model is represented mathematically as:

$$H = \exp\ (a+b/A),$$

where H is height at age A and a and b are constants to be estimated from the data. The exponential function is represented by exp.

This function was fitted to the data from shortleaf and slash pine. Different coefficients were estimated for each species. Figure 2 illustrates the fit of this model to each of the different species. In this case we allowed the shape coefficient, b, to vary by species although this is normally held constant in an anamorphic system. It has been suggested that allowing this shape coefficient to vary is a test for differences in shapes of the height versus age trend. As can be observed in Figure 2, this function is not flexible enough to capture the differences in shape of these two species. The model does not mimic the narrowing of the difference between the two species in the forties. Polymorphic models have been suggested to better describe diverse shapes of height versus age trends.

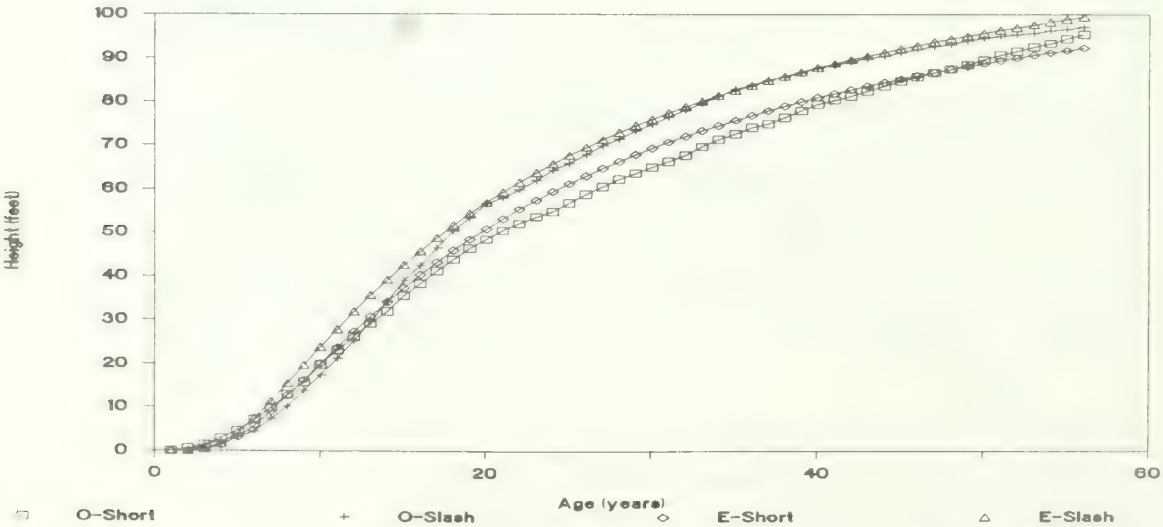

Figure 2. Fit of the anamorphic model for shortleaf and slash pine.

THE POLYMORPHIC MODEL

A typical polymorphic model is the Chapman-Richards equation. This equation can be represented mathematically as:

H = a*(1-exp(b*A))**c,

where H is height at age A. Coefficients to be estimated from the data are a, b, and c. The exponential function is represented as exp. This function was fitted to the data from shortleaf and slash pine. Different coefficients were estimated for each species. Figure 3 illustrates the fit of this equation to the data. This model does a better job of describing the shape of the two curves. It does mimic the narrowing of the difference between species in the forties however it has more curvature than the data in the forties. It is evident that a more flexible model is needed to describe these diverse shapes.

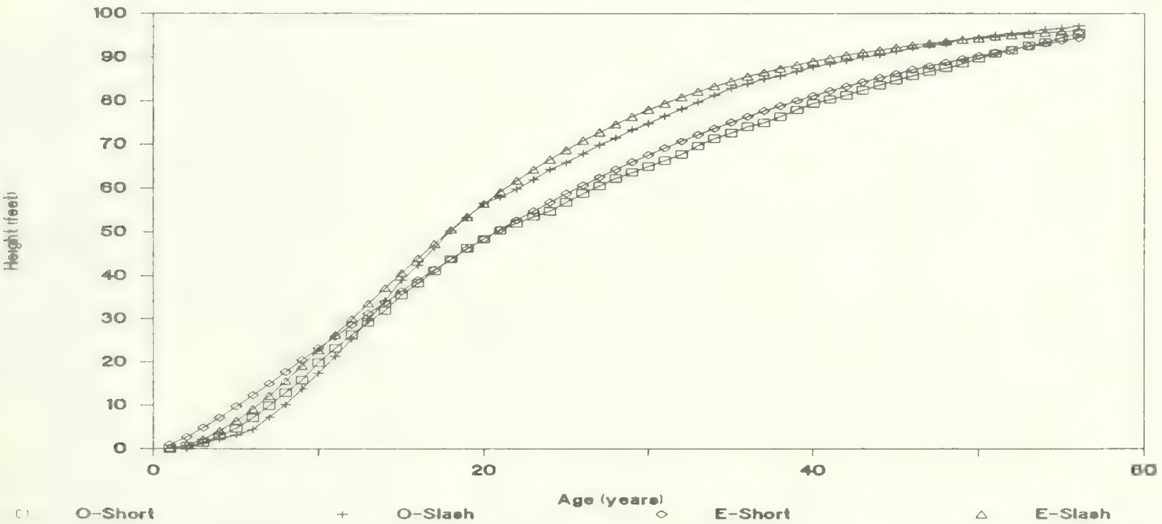

Figure 3. Fit of the polymorphic model for shortleaf and slash pine.

THE PIECE WISE LINEAR GROWTH MODEL

Both the anamorphic and polymorphic models proved inadequate in describing the shape of the height versus age curves. The shape can be mathematically characterized by curvature or rate of change of the first derivative. Height growth is an approximation of the first derivative so rate of change of height growth should indicate curvature or shape of the height age trend. A piece wise linear model fitted to height growth indicates change in curvature through change in slope of each of the linear portions of the model.

Height growth was plotted for each tree and averaged by species. Figure 4 illustrates a typical height growth versus age trend for shortleaf and slash pine along with a piece wise linear fit to the data. Notice distinct breaks in the slope of the height age trend at ages five, eleven, twenty-one and thirty-nine. These same break points were observed for all but three trees and break points for those trees only varied by one or two years. When this piece wise linear growth model was used to forecast height versus age by summing growth, a good estimate of the shape of each species was obtained as is illustrated in Figure 5.

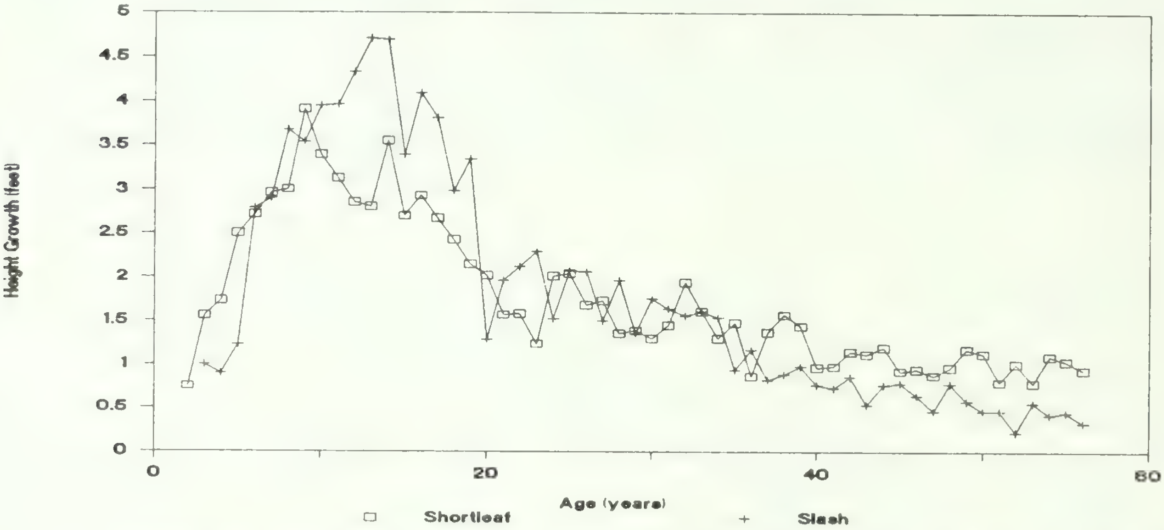

Figure 4. Height growth versus age trend for shortleaf and slash pine.

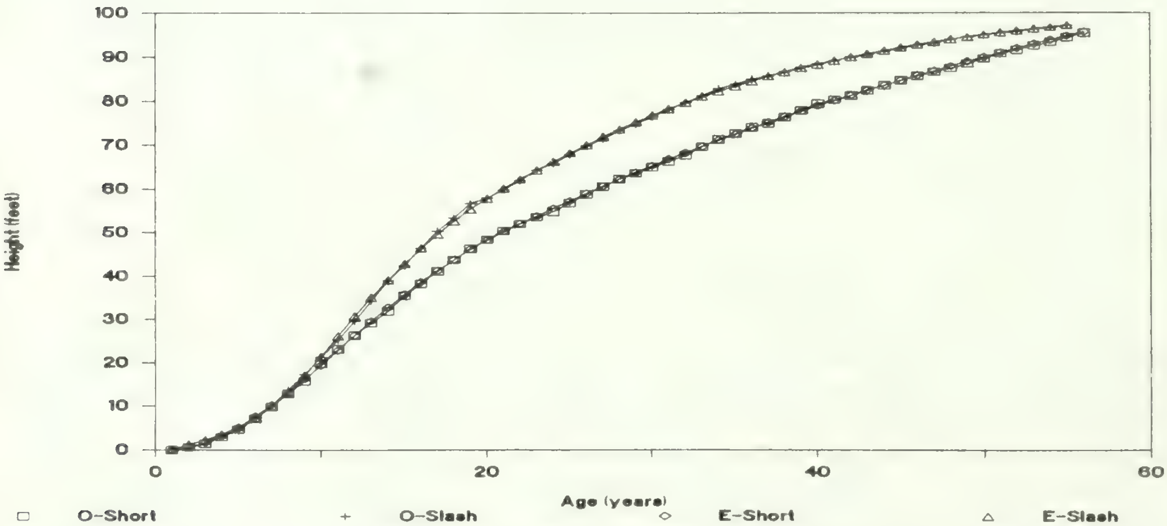

Figure 5. Fit of the piece wise linear growth model for shortleaf and slash pine.

This piece wise linear growth model can be represented mathematically as:

$$G = a*A1 + b*A2 + c*A3 + d*A4 + e*A5,$$

where G is height growth between ages A and A+1,and Ai is equal to A minus the lower limit of the ith interval if age falls in the ith interval. If A is less than the lower limit of the ith interval then Ai equals 0. If A is greater than the upper limit of the ith interval then Ai equals the length of the ith interval. The coefficients a, b, c, d and e are slopes to be estimated from the data. These slopes are estimates of curvature of the height versus age trend in each of the intervals. The intervals are as described above, namely, 0-5, 5-11, 11-21, 21-39, and above 39.

The model is constrained to be continuous, so segments meet at interval limits.

HEIGHT VERSUS AGE TREND SHAPE BY SPECIES

Multiple regression was used to fit the piece wise linear growth model to each tree, to pooled data by species, and all data pooled. Table 1 shows coefficients obtained from the pooled fits by species.

Table 1. Slopes by species for the piece wise linear growth model.

Species	a	b	c	d	e
Shortleaf	0.5010	0.1580	-0.1667	-0.0378	-0.0110
Longleaf	0.4648	0.1845	-0.1102	-0.0716	-0.0264
Loblolly	0.5547	0.2718	-0.2972	-0.0204	-0.0236
Slash	0.3281	0.5269	-0.2556	-0.0788	-0.0233

Loblolly growth accelerated the fastest initially, however slash growth increased even more quickly during the second growth period. Longleaf growth showed a lower rate of decline during the third period, loblolly and shortleaf had modest growth declines during the the fourth period. Shortleaf growth declined the least during the last growth period.

Johnson-Neyman F tests (Huitema 1980) were used to test for significant differences by species and by trees within species. These tests indicated that there were significant differences at the 0.05 level in coefficients between species and between trees within a species. Tests of hypotheses were performed on coefficients fit to individual trees to determine if within tree variation was large enough to mask differences between families. All tests were performed at the 0.01 level. No significant species differences were found during the first, second, or last periods. Significant differences were found during the third and fourth growth periods.

DISCUSSION

Examples of typical anamorphic and polymorphic equations used to describe height versus age trends are not flexible enough to adequately detect differences in curve shape. A piece wise linear growth model is adequately flexible to detect such differences. The coefficients of this model can be interpreted as the curvature of the height age trend, and can directly describe the shape of the curve. Tests of hypothesis on the coefficients can be used to detect statistical differences in curve shape.

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A METHOD FOR LOCALIZING SITE INDEX EQUATIONS

David K. Walters and Harold E. Burkhart[1]

ABSTRACT. Equations for modeling the height-age pattern of forest trees or stands are typically developed for a given species in a specified region. In order to adequately model height-age patterns, the resulting equations are often quite complex. This study presents a procedure for the prediction of height-age relationships through the use of localized equations.

The Schumacher logarithm of height-reciprocal of age model was fitted to data from loblolly pine plantations to attain an average guide curve. This curve was localized to a particular stand by applying Kalman filter, empirical Bayesian, and maximum likelihood procedures. These procedures employ the general concept of feedback in localizing the simple equation. More specifically, as additional information concerning a particular stands height growth development becomes available, it is fed back into the original equation in the form of modified parameter estimates. The Kalman filter model is presented here. It compared favorably with the unadjusted model and a more complex polymorphic equation. The methodology used here to study the pattern of height-age relationships of loblolly pine plantations should prove valuable for other species as well.

INTRODUCTION

Intensive forest management requires the accurate assessment of site quality. Forest land site quality has been evaluated in many ways. The most common and well accepted approach uses the height-age (H/A) development of the dominant stand component as a measure of the quality of the site. When a single height is selected from this H/A curve at age X, this height is known as the stand's site index (index age X). A variety of equation types, and methods of fitting these equations, have been developed. The methods which have been used to develop these curves include graphical (Bruce, 1926), regression analysis (Amateis and Burkhart, 1985; Stage, 1963), segmented regression (Devan and Burkhart, 1982), differential equations (Garcia´, 1983), and others. Good summaries of these methods can be found in Clutter et al. (1983), Carmean (1975), and Hägglund (1981). Early works utilized relatively

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simple equations, such as the log of height - reciprocal of age guide curve to portray height development (Schumacher, 1939). This equation can be used to generate an anamorphic family of H/A curves. In efforts to adequately describe the wide variety of observed H/A patterns, both anamorphic and polymorphic, H/A equations have become increasingly complex. As an alternative to developing more models for smaller regions, the proposal of Turnbull (1978) may be pertinent. He proposed that a full forecasting system should include, among other things: (1) a basic yield model and (2) a feedback model. Munro (1984) agreed with this idea by considering the key characteristic of the "third generation of forest growth modeling" to be the incorporation of a feedback loop.

A feedback model can also be applied to site index estimation. A simple anamorphic equation can be updated or localized with specific sample data; the result may be as good or better than a more complex polymorphic model. This feedback mechanism has already been applied to several forest estimation problems. The objective of this study was to develop and examine a feedback H/A curve.

Various techniques can be used to develop feedback models. Models based on empirical Bayes, maximum likelihood, and filtering procedures were compared and contrasted. These were compared with fit statistics such as average residual, average squared residual, and average absolute residual, and plots of residuals for each model versus several parameters of interest were also examined. The models behaved similarly and the filter model was selected as "best" for several reasons. Filtering is the estimation of the current state of a system contingent upon all prior information and current samples. The specific filter examined here, the Kalman filter, has been used by Dixon and Howitt (1979) in a forest inventory system. Kalman filter theory, most commonly used in the engineering fields, is essentially a sequential implementation of the Goldberger-Theil mixed estimator (Theil, 1963). The Kalman filter is simple and intuitive. It can be expressed in several forms providing mathematical equivalence; thus allowing the user to choose the most computationally efficient form. No assumption was made of the distributional form of the prior or sample data, other than the errors are independent and identically distributed (i.i.d.).

METHODS AND ANALYSIS

DATA

The data used in this study were collected in the 1981-1982 dormant season from loblolly pine plantations on cutover, site-prepared areas in the southeastern United States. One dominant and one codominant tree were felled in each stand. These trees were free of damage and showed no visible signs of suppression. After felling, the trees were

bucked into four-foot sections. The total height and age of each cross-section were then determined. Because of the inability to section trees such that the cross-section falls exactly at the end of a particular years growth, the "bias" correction presented by Carmean (1972) was used to adjust the height of each cross-section. Dyer and Bailey (1987) found this method of correction to be best of six different methods examined. The cutover-site plantation data consisted of 4,231 H/A pairs found on 182 plots (or stands) from throughout the Southeast.

INITIAL MODEL

The linear model;

$$\underline{Y} = X\underline{\beta} + \underline{e} \qquad (1)$$

where $\underline{Y}$ is a vector of log(H) values, X is a matrix consisting of a column of ones and a column of (1/A) values, $\underline{\beta}$ is a vector of unknown regression coefficients, and $\underline{e}$ is a vector of i.i.d. errors, was selected as the general guide curve model to be localized. Only a portion of the 182 plots (referred to as the fitting data) were used in estimating the coefficients of equation (1) and the remainder were reserved for application of the adjustment mechanism and validation.

KALMAN FILTER ESTIMATOR

The Kalman filter estimator can be expressed in several equivalent ways (Didderich, 1985). Several initial definitions must first be presented. Prior information is expressed by the equation:

$$\hat{\underline{\beta}}_p = \underline{\beta}_p + \underline{e}_p \qquad (2)$$

where $\underline{e}_p$ is a vector of i.i.d. random errors with mean $\underline{0}$ and covariance matrix W_p, and $\underline{\beta}_p$ is a vector of coefficients for some linear model (equation (1) in this case) based on the prior information data set. The sample information is expressed as:

$$\underline{Y}_s = X\underline{\beta}_s + \underline{e}_s$$

where $\underline{e}_s$ is a vector of i.i.d. random errors with mean $\underline{0}$ and covariance matrix W_s, and $\underline{\beta}_s$ is a vector of estimated coefficients based on the sample data set.

The additional assumption that $\underline{e}_p$ and $\underline{e}_s$ are uncorrelated is also placed on this system.

The Kalman filter estimator is:

$$\hat{\underline{\beta}}_{kf} = \hat{\underline{\beta}}_p + K(\underline{Y} - X_s\hat{\underline{\beta}}_p) \qquad (3)$$

$$\text{where: } K = W_p X'_s [W_s + X_s W_p X'_s]^{-1}$$

An alternative expression for $\hat{\underline{\beta}}_{kf}$ is:

$$\hat{\underline{\beta}}_{kf} = Q_s \hat{\underline{\beta}}_s + Q_p \hat{\underline{\beta}}_p \qquad (4)$$

$$\text{where: } Q_s = [X'_s W_s^{-1} X_s + W_p]^{-1} [X'_s W_s^{-1} X_s]$$

$$Q_p = [X'_s W_s^{-1} X_s + W_p]^{-1} W_p^{-1}$$

Q_s and Q_p are proportional to the inverse of the variance of $\hat{\underline{\beta}}_s$ and $\hat{\underline{\beta}}_p$, respectively. These two expressions are equivalent and are the best linear unbiased estimators (BLUE) for the combined prior and sample information.

As seen from equation (3), $\hat{\underline{\beta}}_{kf}$ can be expressed in a sequential fashion:

$$\hat{\underline{\beta}}_i = \hat{\underline{\beta}}_{i-1} + K(\underline{Y} - K\hat{\underline{\beta}}_{i-1})$$

where $\hat{\underline{\beta}}_i$ is an estimate of $\underline{\beta}$ for plot i and $\hat{\underline{\beta}}_{i-1}$ is and estimate of $\underline{\beta}$ for plot i-1, and K is the Kalman gain matrix as defined earlier.

Diderrich (1985) shows that the updating step of a Kalman filter is equivalent to the Goldberger-Theil mixed estimator commonly used in econometrics (Theil, 1963).

COMPARISON MODEL

As a comparison, a number of more complex, polymorphic models were examined. The model from Amateis and Burkhart (1985) performed best for these data. This equation is fitted in a difference form and the final equation, replete with coefficients calculated from the fitting data, is :

$$\log(H) = \log(S)[A_i/A]^{-0.1091} \exp(-2.0142[A^{-1} - A_i^{-1}]) \qquad (5)$$

where A_i is index age and S is height at that age.

RESULTS

Comparisons were made of the three alternative H/A models (equations (1), (3), and (5)). The first approach to comparing the models was an overall aggregate approach in which the three models were compared, using validation data, with the following statistics:

Overall Plot-level Bias (OPB)

$$(100/n_p) \sum_{i=1}^{n_p} [(H_i - \hat{H}_i)/H_i]$$

Overall Section-level Bias (OSB)

$$(100/n_s) \sum_{i=1}^{n_s} [(H_i - \hat{H}_i)/H_i]$$

Overall Mean Bias by plot

$$(100/n_p) \sum_{i=1}^{n_p} [(1/n_s) \sum_{j=1}^{n_s} [(H_{ij} - \hat{H}_{ij})/H_{ij}]]$$

These values are presented in Table 1 for each model.

TABLE 1. Aggregate statistics for the three models.

Equation Number	OPB (Variance)	OSB (Variance)	OMB (Variance)
(1)	4.5894	-0.3109	0.4435
	(20.84)	(46.82)	(10.87)
(3)	4.4124	-0.2387	0.4421
	(21.42)	(47.11)	(10.86)
(5)	1.4992	1.0306	1.2650
	(24.60)	(45.27)	(8.93)

The second criterion (OSB) may be more appropriate when examining alternative models in light of their possible applications. Only trees for which an observation was available at ages 3, 5, 10, 15 , and which were at least 20 years of age were evaluated. Two scenarios were considered. The first scenario was the case where tree height at age 10 is known. Equation (3) is adjusted using the previously observed height measurements at ages 3 and 5. The second scenario assumes that the height at age 15 is known and adjusts with previously observed heights at ages 3, 5, and 10. The mean residuals, mean absolute residuals, and the variance of these residuals are presented in Table 2.

Figure 1 presents equations (1) and (3), along with the actual height values, for a randomly selected tree and shows clearly the ability of the equation (3) to more closely follow the actual H/A pattern.

TABLE 2. Application-oriented statistics for the three models.

Equation Number	Mean Residual	Mean Absolute Residual	Variance of Residual
Height Known at Age 10			
(1)	- 8.11	11.67	147.10
(3)	- 5.64	11.37	182.10
(5)	-14.15	14.70	220.39
Height Known at Age 15			
(1)	- 1.70	3.81	18.10
(3)	- 1.29	3.35	17.30
(5)	- 7.56	7.56	13.34

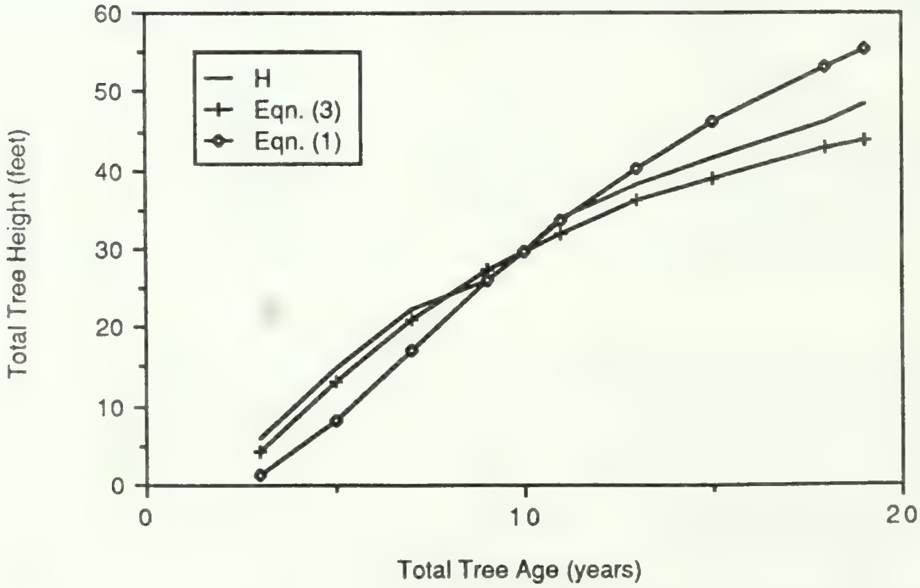

Figure 1. A comparison of equations (1) and (3) with the actual H/A pairs for a randomly selected tree. Equation (3) is adjusted with the observed heights at ages 3, 5, and 10.

CONCLUSIONS AND APPLICATIONS

Three models for predicting the height-age development of forest stands: (1) a simple anamorphic model, (2) a polymorphic model, and (3) a feedback model, were examined using stem analysis data from loblolly pine. The feedback model presented here is based on Kalman filter procedures. This model is dependent upon having prior information about the height-age relationship in the form of an estimate of the coefficient vector and the variance of this estimate. The initial equation is then updated with this additional information. This information can be either stem analysis data, as in this case, or repeated plot-level measurements. The Kalman filter model improves upon both the unadjusted H/A model and a more complex polymorphic model, as judged by various fit statistics.

Several possible applications exist for the feedback model presented here. If information on a large scale is unavailable for a specific area but information about similar areas is available, the height-age pattern in the specific area can be estimated better via this method.

As specific examples of the use of this model, several scenarios were explored in which the height of a tree is known at a specific age, and there are various amounts of additional information available. The Kalman filter estimator compared favorably in these various scenarios.

Many models of forest growth are plagued by the problem of the predictions being inconsistent with newly obtained sample data. By incorporating these samples into the prediction process, this inconsistency can be ameliorated to a certain extent. The H/A pattern of a stand, being vital to predictions of yield, is a logical place at which this incorporation should occur.

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SOUTHERN FOREST GROWTH TREND ANALYSES TO EVALUATE AIR POLLUTION INFLUENCES--A PROGRESS REPORT

Tommy R. Dell[1]

ABSTRACT. Allegations of a decline in forest growth related to wide-area atmospheric pollution influences in the Southern United States have prompted us to identify, edit, and analyze existing plot information. The objective is to develop data bases and analytical processes to independently determine if there is a growth decline in the South that is not readily explained by stand and weather variables. The project is a series of research efforts involving multiple data sets and forms of analysis. Five USDA Forest Service Southern Station units and two Southeastern Station units are taking part. A cooperative agreement with Robert Zahner of Clemson University in South Carolina is being used to define a weather variable to be employed with stand variables in refining growth predictions.

The bulk of the information for our analyses is from remeasurements on six major data bases from research growth and yield (RGY) type plots involving plantations of the four major southern pines, plus naturally regenerated stands of longleaf and of loblolly pines. Some USDA Forest Service Forest Inventory and Analysis (FIA) data are also being analyzed. Thus far we have edited and accepted into our data bases information on 25,669 plot growth periods, 607,114 d.b.h. measurements, and 829,242 tree height measurements. Each of the plantation data sets reasonably covers the current distribution of that species. Some data sets have sufficient diversity in time to allow contrasts of time periods. This project will result in a series of separate analyses to be finalized and reported during 1988. Related evidence on the growth decline question will be summarized, and guidance will be given for future monitoring of forest responses to atmospheric pollution.

INTRODUCTION

Wide-area, as opposed to point-source, pollution influence on forests is a major current concern. There has been a change in focus from site-specific cases to situations involving broad areas and long-term exposures to multiple pollutants with perhaps subtle influences on forests (McLaughlin 1985). In contemplating the threat of an ecosystem decline, Bormann (1985) noted the difficulties of detecting trends due to natural variation in ecosystems and the lack of pollution level information. Data and models for defining pollution levels in rural areas are inadequate, but it is certain that pollution is increasing in the South, and much attention is given to ozone as the harmful agent. For the South, the highlands through the northern-most States have

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threatening ozone concentrations at times, but the coastal areas of Texas and Louisiana that coincide with major petroleum processing facilities are rated as more critical by some observers.

If site-specific cases are omitted, there is no firm evidence of wide-area atmospheric pollution influences on forests in the South (Lucier 1986). Although published and unpublished background indicates that certain families of white pine (Pinus strobus L.) show extreme sensitivity to pollutants, information on field studies is limited. Selection for resistance to pollution has undoubtedly taken place in some naturally and artificially regenerated white pine stands in the fallout zones of specific sources of pollution.

In the Southern Forest Growth Trends (SFGT) Project, we are utilizing a retrospective field plot approach that involves remeasurement data from trees grown in a forest setting. Some of our analyses will utilize data from the FIA samples, but most will rely on data from repeatedly measured RGY plots initially installed to measure growth in selected or created forest conditions. This approach is very different from the more controlled, dose-response type studies. Hopefully, controlled condition studies and processes of extrapolating related results to actual forests will evolve and be linked with sets of plots designed for future monitoring. However, at the present time, data taken from our past studies must be utilized to provide initial guidance and model formulation.

The definition of the South used here is the one employed by FIA; it includes the south-central region consisting of Tennessee, Alabama, Mississippi, Arkansas, Louisiana, Oklahoma, and Texas. Also included are the States of Virginia, North Carolina, South Carolina, Georgia, and Florida in the southeastern region. Across the South, pines tend to dominate in the Atlantic and Gulf Central Plains, and upland hardwoods occupy the highlands comprising the northern and western boundaries. Transecting these two forest types is a pattern of major river systems containing the third broad forest type, bottomland hardwoods. Currently the South provides 45 percent of the nation's domestic timber production and has 182 million acres of timberland, about 10 times the timberland of West Germany. Nearly half the South's timberland has some pine or is suited to pine production. For this portion, management activities are generally directed at establishing and maintaining pine dominance. The wood-using industry and total commercial interests are far more developed in the pine type than in the hardwoods. Over 85 percent of the money paid for stumpage in the South goes for pine. Pine plantations, particularly loblolly pine plantations, are becoming increasingly important.

Perhaps the most important thing about southern pines is their potential to grow rapidly. In most forestry enterprises of the world, the accumulated volume of wood and the economics of harvesting are absolutely dominant factors. But in the South, the pine growth potential and the expectations of future wood supplies provide the stable basis for commercial developments. Any threat of a growth decline must therefore be taken very seriously.

ORGANIZATION AND APPROACH

The SFGT project is a series of research efforts involving multiple data sets and forms of analysis. We realized that a great deal of data and expertise were on hand, and with modest supplemental funding questions regarding the influence of atmospheric pollution could be addressed. We expect that the researchers and data sets involved will benefit from this venture, and there will be no significant disruption of other scheduled research. Most of the work is being done by people in temporary positions established at six locations throughout the South. Two university cooperatives are also being utilized, and provisions were made to expand data processing capabilities. Directors of both the USDA Forest Service Southern Forest Experiment Station (SO) and the Southeastern Forest Experiment Station (SE) have given good support in identifying data sets that might be of use in such growth and yield type studies.

The effort currently involves five SO and two SE units as follows:

- SO 4101 Silviculture of the Southern Pines
- SO 4106 Timber Management of Nonindustrial Properties
- SO 4107 Quantitative Studies for Forest Management
- SO 4108 Genetics of Southern Pines
- SO 4801 Forest Inventory and Analysis for the Midsouth
- SE 4103 Loblolly Pine Stand Management
- SE 4104 Stand Establishment of Loblolly Pine.

Levels of activity vary greatly among these units, with some simply providing data while others are employing full-time researchers. We are also working directly with the SE FIA unit in joint analyses of FIA data from the two stations.

It is essential to understand the differences in the two kinds of data alluded to earlier (FIA and RGY) to comprehend how they can be used to answer growth trend questions. FIA data involves samples at arbitrary grid locations with remeasurements generally at 10-year periods; there is no control of activities, such as thinning on the plots between measurements. The major objective is to get representative data for the forest at different times and to make generalizations about the complex forest population at each time.

In contrast, RGY emphasized a more elaborate consideration of stand developments in selected or experimentally created situations that are of particular interest, with remeasurements at 5-year intervals. For example, data had been accumulated on pine plantations long before they were prevalent enough to be expressed in survey data. Activities such as thinnings are controlled so that measurements are made on the residual stand at the start of a period of growth. Most RGY modeling has dealt with the simple stand circumstances of pure, even-aged stands. The variables generally used to model or predict growth, such as age and site index, are readily determined. Growth and yield models today cannot handle the complex stand structure common in FIA data.

Some form of modeling or adjustment is necessitated by questions such as: "Have trees in otherwise comparable circumstances grown slower in

recent years?" Since models are not developed for complex situations, we have been forced to take subsets of the FIA data. An example is even-aged loblolly pine on plots that were not "disturbed" by cutting during the growth period. This makes the adjustment to comparable situations easier but eliminates the direct unbiased generalization to large areas of complex forest. It also raises the threat that biases will be introduced by selecting plots that were undisturbed. Actually, the selected subset of FIA data is much like the larger collection of RGY data that has accumulated over the past 50 years to answer growth questions. Most of the effort of the SFGT project is directed at getting these RGY data bases analyzed and to formulate variables that express weather influences. All of this necessitates our locating the growth observations in time and place; in the past we dealt only with growth values as functions of stand variables. If levels of pollution estimates are made available for given places, times, and pollutants, we will be in a good position to evaluate associations with the residuals from our predictions based on stand and weather variables. If pollution level estimates cannot be defined, we will make contrasts of growth rates in earlier and later time periods, with time thus serving as a surrogate level-of-pollution factor. In either case, considerable information will be provided on the initial question of, "Is there really a decline to be explained?"

PROGRESS ON DATA BASES

By pooling data from many studies, we have identified seven major data bases as listed in table 1 with the number of variable entries that have been edited and accepted into the data bases thus far. Initially, we sought a hardwoods data set but could not find enough established, long-term RGY plots. Plots of naturally regenerated pines are limited, relative to the plantation information, but with each species there is the potential of some contrast of growth in periods of time.

Table 1.--Information accumulated to date on the seven major data bases.

Major data base	D.b.h.	Tree height	Plot growth period
	Number of measurements		
Loblolly plantations	186,857	299,146	10,420
Shortleaf plantations	99,256	201,826	5,640
Longleaf plantations	86,399	150,100	3,498
Slash plantations	94,332	125,143	4,039
Natural longleaf	68,800	13,700	800
Natural loblolly	41,770	18,327	432
SO FIA	29,700	21,000	840
Total	607,114	829,242	25,669

This is undoubtedly the largest aggregation of southern pine plantation data that has ever existed. We have put together data sets in the past to develop various growth and yield systems, but we have never

attempted data aggregations and analyses of the scope required here. Fortunately, in the last year, long-term efforts to get adequate software and hardware at SO research centers has resulted in SAS software being available with large capacity, low-cost computers for each of the participating scientists. A major accomplishment of the SFGT project has been the intensive computer based editing and recomputation of plot variables that could not have been carried out in the past.

Figure 1 shows the counties where we have RGY plantation data for each of the four major southern pine species. There are extreme concentrations of plots in certain counties to facilitate the work in some studies. However, generally the coverage is good for each species, and numerous plots are included in each location. The real strength of these plantation data sets is in the diversity of location.

The FIA data shown in table 1 concerns naturally regenerated loblolly pine of central Alabama and a contrast of the 1962-72 and 1972-82 periods. The dominant trend is that larger trees and higher volume to basal area ratios are prevalent in the more recent period. With volume growth per acre as the response, various analyses of covariance using site class, stand size (a surrogate for age), and a density variable could show no difference in growth by time period. It was convenient to get basal area at the end of the growth period from existing FIA computer files for the density variable. Some reviewers felt that basal area at the start of the growth period was a more appropriate measure of density for the period; therefore, we are currently getting additional data to rerun the covariance analyses. If the covariates are ignored, the observed volume growth rates are actually significantly higher in the most recent period. When the radial growth by diameter classes for the two periods is contrasted without adjustment for site, age, or density, there is a trend of lower radial growth for < 9-inch d.b.h. tree classes. However, this is to be expected when the stands tend to be larger and older in the more recent period. A 6-inch d.b.h. tree in a young stand is a front runner, but in an older stand it will be suppressed.

As the tree data bases were being edited, progress was made through a cooperative agreement with Robert Zahner of Clemson University to consider weather influences on growth. His work with us involved three aspects: (1) the analysis of a naturally regenerated longleaf pine study in southern Alabama with very elaborate tree growth and weather data at one location, (2) development of processes and software to take standard weather records in the vicinity of any plot in the South and compute indices of "growing days" for any year, and (3) evaluation of a variety of weather variables from the longleaf study using different levels of aggregation in both time and place.

ANALYTICAL PROCESSES

Over the past year, along with the data editing and weather variable formulation, we have had periodic sessions with researchers to define meaningful analyses and identify potential pitfalls in our interpretations. Analyses to contrast time periods such as have been

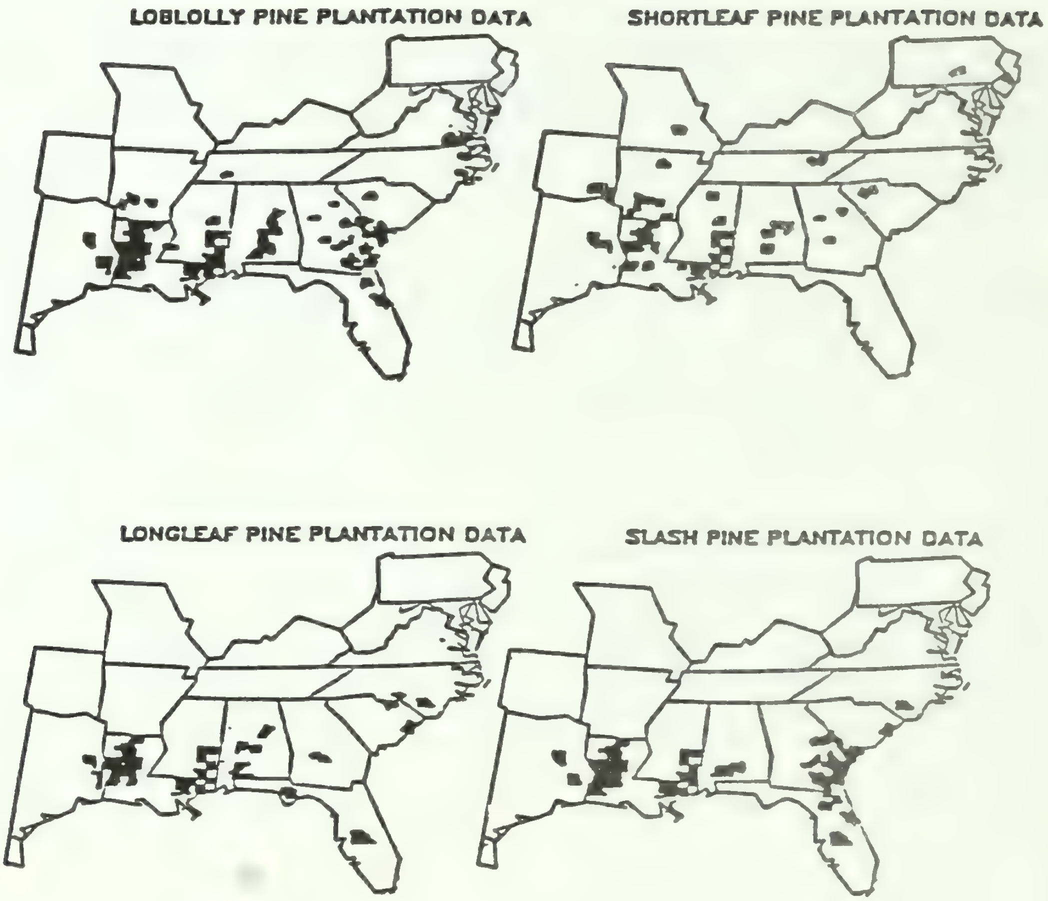

Figure 1. Counties with research growth and yield plantation plots for each of the four major southern pine species.

explained for the FIA data and the southern Alabama longleaf pine data seem clear, but other questions are not easily resolved. One concern with using growth and yield type models to explain or predict growth is that the driver variables, such as number of surviving trees or height of the dominant stand, could indeed have been altered by air pollution. In adjusting for site and density with the hope of getting a better fix on a pollution influence, we might unknowingly take out the direct influence of pollution. Thus, we will do preliminary tests of hypotheses for changes in survival and height over-age patterns associated with pollution.

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MODELING THE INFLUENCE OF POLLUTION ON ALLOCATION

E. David Ford and Susan Bassow[1 2]

ABSTRACT. Four criteria are suggested for models designed to simulate the effects of pollutants upon forest growth processes. They should i. predict timber yield, ii. be responsive to the cumulative effects of pollutants, iii. simulate chronic effects, and iv. be able to examine different theories of pollutant influence. Modeling the allocation process is central to such models and must describe priority in allocation between meristems, respiration, and growth features that may be impacted by different pollutants. A Model development with these features is outlined and some results described.

INTRODUCTION

The Forest Response Program of the National Acid Precipitation Assessment Program is an inter-agency (EPA, Forest Service, NCASI) initiative to assess possible impacts of "acid rain", alone or in combination with other pollutants, upon forest growth. The program supports work in modeling the physiological response of trees to pollutants through simulation for two purposes.

Firstly, in regions where pollution is considered chronic rather than acute, direct observations of change in tree and forest growth rate in relation to changes in pollutant loading have proved difficult to study by such methods as inventory assessment to tree ring analysis. A possible reason for this may be that both foliage, particularly of conifers, and the soil-root system may respond slowly, but cumulatively to some pollutants.

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Reich (1987) synthesized experimental evidence on the effects of ozone on carbon balance and growth of evergreen conifers, deciduous hardwoods, and agricultural crops. Ozone uptake and physiological responses can be predicted from leaf diffusive conductance. Conifers are the least sensitive of the three groups on a calendar time scale (by a small margin), but they are most sensitive on a relative (leaf life span) time scale. In an analysis of the effects of air pollution on coniferous forest growth in Finland, Hari, Raunemaa and Hautojärvi (1983) estimated that acidification affects forest nutrition on sandy soils, but that the ion exchange process may generate a time lag between acid deposition and its effect which they estimated as 20 ± 10 years.

A real difficulty in assessing the influence of pollution on trees and forests is that it may be a slower process compared with that upon arable crops. Assessment then has to be made over a number of years and consequently, must be measured against i. variation in response to changes in the natural environment and ii. the normal process of growth and decline that can be observed in any forest stand. These latter changes are the result of dynamic processes within the tree and the stand as a distinct microclimate is generated (Ford 1984).

A second reason for simulating the physiological response of trees and forests to pollutants is that pollutant loads are not constant. Indeed, legislators may wish estimates of the possible effect of a range of policy decisions that could result in different loadings. This requirement places very stringent demands upon our understanding of the dynamics of forest growth and how this might be influenced by pollutants.

OBJECTIVES AND CRITERIA FOR MODELING THE INFLUENCE OF POLLUTANTS ON TREE AND FOREST GROWTH PROCESSES

The requirement for simulation models of forest response to pollutants arises because we recognize that forest growth processes change slowly and that changes may be difficult to detect by traditional growth measurements made in a statistical framework. Yet, we must be able to predict the cumulative effect of these slow changes. With this in mind we can specify four criteria for this type of modeling:

i. Objective Models must predict timber growth. We anticipate using these models at least as an adjunct, if not in place of, traditional mensuration and prediction techniques. This sets a clear requirement that models must predict the production and allocation of carbohydrate and its formation as timber.

ii. Structure Models must be responsive to cumulative effects, both of damage and potentiality of repair. The mechanism through which pollutants may cause a change in timber production must be described. This involves aspects of tree physiology and stand microclimate.

iii. Accuracy. The principle problem in assessing pollution is to estimate the possible existence of chronic effects and to devise ways in which such effects may be described.

iv. Relation to theory. Physiological based models must be able to test theories on the mechanism of influence of pollutants upon tree and stand growth. This requirement, along with the objective to predict timber yield, gives physiological based models a clear direction and can be used in the definition of bounds to the model. It also implies that since there is more than one "theory" there is likely to be more than one model.

MODELING ALLOCATION IN WOODY PLANTS: SOME FUNDAMENTAL CONCEPTS.

We use the word "allocation" to describe the process of distribution of photosynthate between the different plant meristems: foliage, stem and root thickening, fine root, and reproductive tissue. In considering the total carbon balance of the tree, respiration must also be included. Different proportions of plant parts have been measured in forests of different species (e.g. Cannell 1985), and forests of the same species growing under different environments (Keys and Grier 1981, Linder and Axelsson 1982). Most importantly, proportions have been found to change as forests age. In particular, woody biomass increases relative to foliage and fine root amounts. Allocation is an important concept which integrates growth physiology into the resulting structure of forests. Modeling forest growth at this level meets the first criterion specified in the previous section.

There are three important concepts to consider in modeling the allocation process.

i. Priority of distribution between meristems. For example, it is frequently assumed that stem thickening has a lower priority than foliage increment although no clear limits can presently be set to that priority.

ii. Respiration, and particularly the concept of maintenance respiration, can have a major influence on carbon balance predictions. Maintenance respiration assumes that to continue to stay alive all tissues consume some proportion of photosynthate. If this value is calculated as $weight.weight^{-1}.time^{-1}$ then, as a tree gains in size, an increasing amount of photosynthate is consumed for respiration, unless respiration rate decreases. This is still an area of imprecise measurement.

iii. Process identification. In modeling allocation to assess possible influences of pollution, it is important for the structure of the model to treat the different features of physiology and stand development, which are thought to be impacted by pollution, as separate and not aggregated functions.

A MODEL FOR ALLOCATION SENSITIVE TO THE INFLUENCE OF POLLUTANTS

A complete review of models of allocation and growth cannot be attempted here, but the recent contribution of McMurtrie and Wolf (1983) is a starting point. They modeled the carbon budget of a forest as a set of simple differential equations. Their model assumed constant allocation to different plant parts over the life of the stand and mortality was included with respiration loss from the same tissues. The principal result from their model was the prediction of stand mortality as respiration from woody tissue received an increasing proportion of photosynthate produced. When less allocation was made to roots, greater stem growth was obtained (a simulation of the result of Keyes and Grier (1981) and Linder and Axelsson (1982)). Two structural features of their model that make it difficult to use to estimate pollution effects are that foliage was not categorized by age and that once a maximum foliage amount was attained then foliage increment was assumed equal to foliage death.

The model schematic given by Fig. 1 describes the dynamics of tree growth through the same basic physiological processes as McMurtrie and Wolf (1983); however, the structure of the model is more complex and incorporates features necessary to model some theories of pollution influence. Foliage is distributed by age, with each age having a different photosynthetic rate and mortality function. The priority in allocation is given first to satisfy respiration, C1 (Fig.1), which is modeled separately from mortality. Each tissue category can have a different respiration rate. The second priority is to foliage. Three limits are placed upon its growth i. An annual increment

may only exceed the previous years by a certain factor, C2, an attempt to simulate the branch support requirement. C2 declines as size canopy increases. ii. To simulate light or water limitation a maximum foliage amount is assumed, C3. Annual foliage mortality increases proportionally as the maximum value is approached. iii. Foliage increment can never exceed a certain proportion of the photosynthate that remains after the respiration requirement is satisfied. This simulates the balance of photosynthate distribution attained through seasonality.

Allocation to fine root maintains a specific fine root: total foliage ratio, C4. This assumes a necessary balance is maintained between root and shoot. Allocation to fine root will increase if root mortality increases, C5, but canopy size stays large. The photosynthate that remains after all of these processes are satisfied is allocated to woody tissue.

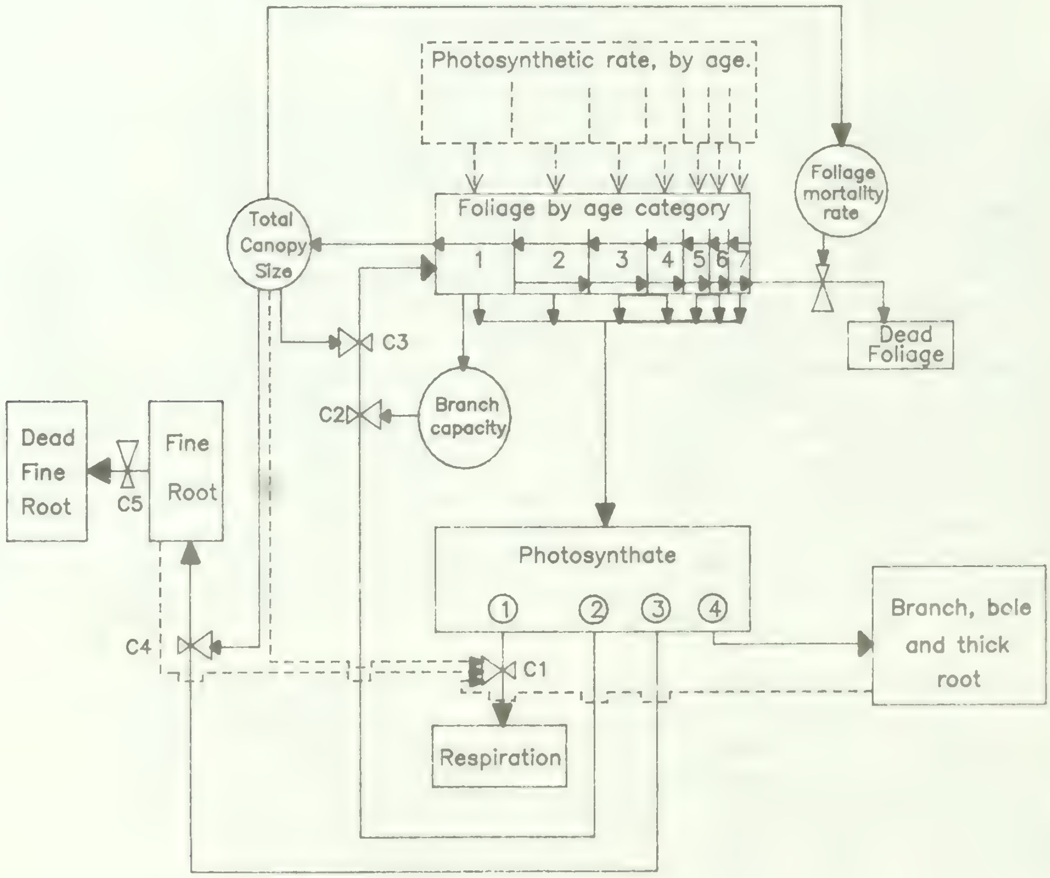

Figure 1: Schematic of tree growth model.

The most difficult aspect of the forest growth mechanism to simulate is foliage development. Fig. 1 represents an attempt to describe mechanism at the stand level that are really properties of the individual tree and crown. The behavior of the model can be critically influenced by values used for C2, the limits set by branching structure, and C3, maximum size. These constraints on growth of foliage have a rational basis but further modeling of this aspect of forest growth is essential at the branch and crown development level and is in progress.

To illustrate some aspects of the behavior of the model described in Fig.1, parameters for C1-C5 were estimated from Ford (1982) and unpublished data. These cannot be described here in detail; it is more appropriate to give some important general results (Fig. 2).

The oscillatory nature of total foliage amount, Fig. 2., is the result of a simulation making annual increments of a continuous process - but trees do grow in seasonal increments! Note the increase in total respiration rate in the life of the stand.

A pollution effect operating through foliage is simulated by decreasing photosynthetic rates at all ages by 10 percent and increasing annual foliage mortality by 10 percent (Fig. 2b). The build up of foliage was markedly delayed and less wood was produced. A pollution effect operating through root mortality and therefore increased allocation to fine root growth was simulated by increasing annual root mortality from 0.4 to 0.6 of stand root amount throughout the life of the stand (Fig. 2c). This resulted in decreasing allocation to wood early in the life of the stand and so a decrease in the total stand respiration over its lifetime and very similar total wood produced to that in Fig. 2a.

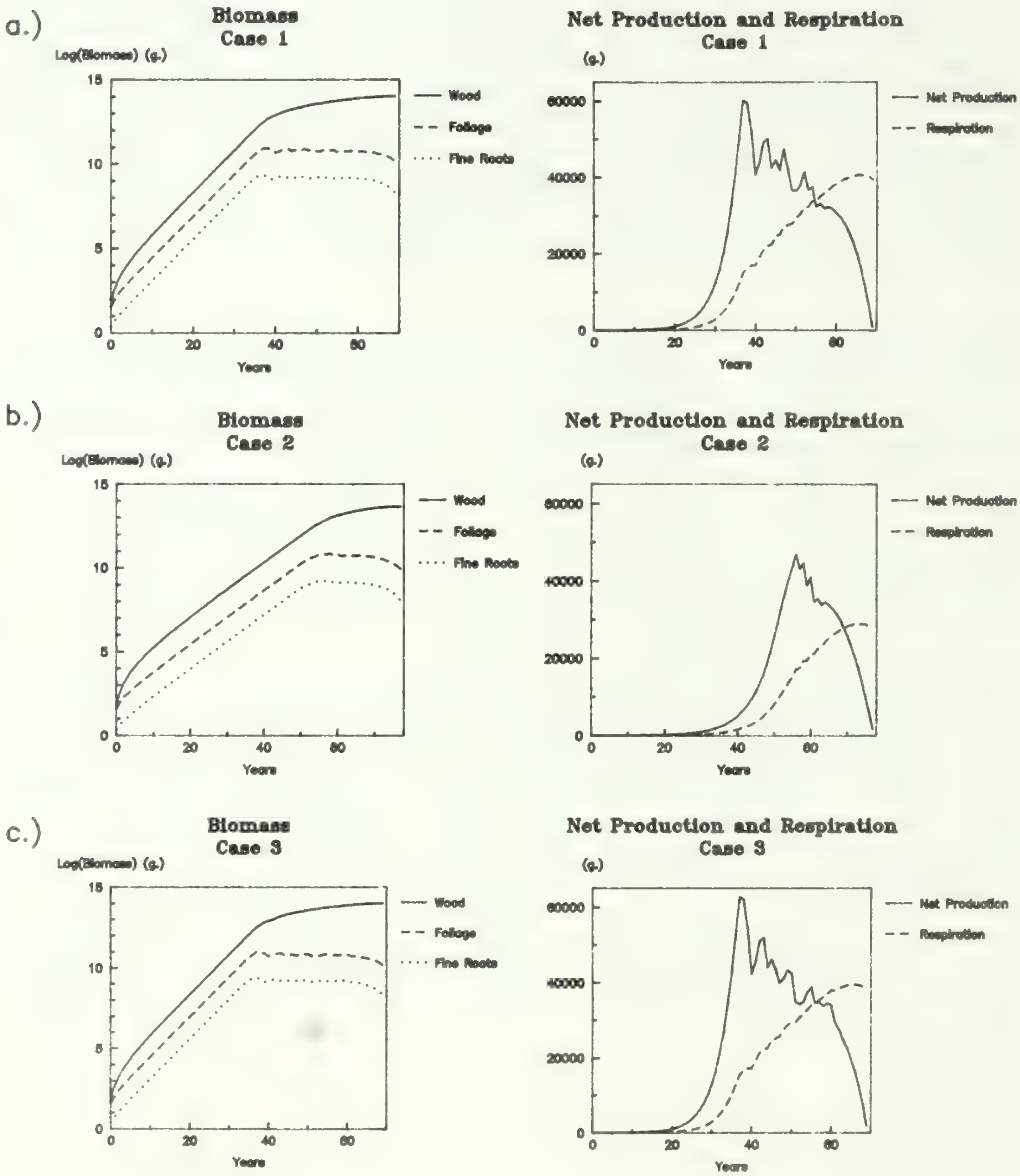

Figure 2: Output from tree growth model. Case 1 uses the basic parameter values. Case 2 has decreased photosynthetic rate, and increased foliage death rate. Case 3 has increased root mortality.

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AN EVALUATION OF METHODS FOR ASSESSING IMPACTS OF PESTS ON FOREST PRODUCTIVITY

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ABSTRACT. This paper evaluates the merits and possible weaknesses of three methods for estimating forest pest impacts: surveys, growth and yield models, and controlled experiments. When precise impact information is needed to evaluate cost-effectiveness of pest management options, growth and yield models that incorporate pest incidence parameters as modifiers of yield, or controlled impact experiments, need to be considered. When these methods are feasible, they should provide greater accuracy than surveys because they measure long-term growth compensations for trees killed by pests.

INTRODUCTION

Insects, fungi, and other organisms that reduce production of wood fiber are considered "forest pests," and the damage they create is commonly labeled "pest impact." This impact may result from tree death, growth loss in surviving trees, or defects that reduce the value of the wood in trees. Pests also may adversely alter esthetic, recreational, or other less tangible values. Considerable effort has been spent in trying to quantify the impacts of many forest pests. In principle, this effort is well justified because timely and effective pest management will ultimately depend on accurate quantification of impacts and determination of whether costs of proposed actions are likely to be less than the value of the resource being destroyed. However, in spite of the need and the effort made to quantify pest impacts, there is general dissatisfaction with both the methods currently used to assess impacts and the reported values. This paper looks critically at the status of pest impact assessment, with emphasis on production of wood fiber. We will concentrate largely on the strengths and weaknesses of three methods for assessing these impacts--survey, growth and yield modeling, and controlled experiments. The discussion will be drawn mostly from personal experiences with fusiform rust of southern pines, a serious canker disease caused by the fungus *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*.

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THE ROLE OF SURVEYS IN FOREST PEST IMPACT ASSESSMENT

The method used almost exclusively to estimate forest pest impacts is survey. The procedure involves the establishment of a number of plots or observation points--usually temporary in nature--on which incidence of visible damage is quantified. Surveys may be conducted to estimate the damage caused by a specific pest. For example, periodic aerial surveys are conducted to detect areas of damage caused by the southern pine beetle (Dendroctonus frontalis Zimm.). These flights are followed by field surveys to measure the affected trees and to develop control recommendations. The Forest Inventory and Analysis groups of the USDA Forest Service periodically collect damage information for many pests on survey plots established to estimate the quantity and quality of the nation's forest resources.

Surveys can indeed provide valuable information. By defining the present quality of resources, they point to potential gains that might be achieved through more intensive management. Surveys also should provide a good perspective of the relative importance of different pests. When repeated at intervals, surveys may show whether damage is increasing or decreasing. Whether survey data are adequate for judging pest impacts will depend, however, on the nature of each specific pest problem. To illustrate, let's contrast Dutch elm disease with fusiform rust of southern pines.

The Dutch elm fungus, Ceratocystis ulmi (Buism.) C. Moreau, kills more or less isolated, mature elms (Ulmus spp.) in urban or forest settings. To estimate the total impacts of the disease, one might consider the estimated value of each dead urban elm, the costs of removal and replacement, and perhaps the comparative values of trees that replace the dead elms in the forest. Most likely, a hundred different investigators would come up with an equal number of different procedures and answers to this problem. But for practial purposes, all we may need to know about this disease is the number of trees killed annually by geographic area. Since surveys can provide this information, survey data should adequately depict the impact of Dutch elm disease.

In contrast, fusiform rust infections occur mostly in densely planted, pure stands of 1- to 5-year-old loblolly pine (Pinus taeda L.) or slash pine (P. elliottii Engelm. var. elliottii) in the Southern United States. Infections after age 5 are infrequent and much less damaging. Galls or cankers may develop directly on the main stem or branch infections may spread into the stem. Such stem-infected trees often die before they can be harvested, and surviving infected trees may yield forest products of reduced value. Since the fungus spreads from pine to oak and then back to pine, but never directly from pine to pine, the disease tends to be randomly distributed, rather than clustered. While losses at times are as catastrophic as for any forest disease, most typically we are dealing with 10 to 50 percent stem infection by age 5 in plantations with 300 to 700 pine stems per acre.

The usual survey procedure for estimating impacts of pests like fusiform rust is essentially to equate the impact with the visible damage. Such information may be misleading, however, because it fails to consider

that time often mitigates pest impacts. When trees in forests compete strongly for growing space, death or removal of some trees may stimulate growth of remaining trees. To account for the effects of time, one must measure or estimate yields of affected stands with and without pest damage. Such estimates require approaches other than survey.

GROWTH AND YIELD MODELS FOR ESTIMATING PEST IMPACTS OR YIELDS OF FORESTS WITH PESTS

A recent trend in forest pest impact assessment is the development of growth and yield models for estimating yields of forests with pests. Perhaps the best known precedent for this approach is that for predicting yield of stands of ponderosa pine (P. ponderosa Dougl. ex Laws.) or lodgepole pine (P. contorta var. latifolia Engelm.) infected with dwarf mistletoe (Arceuthobium vaginatum subsp., cryptopodum (Engelm.) Hawksw. & Wiens) (Edminster 1978, Myers et al., 1971, 1972).

In another example, Nance et al. (1983) modified an existing growth and yield model (Dell et al., 1979) to predict effects of different intensities of fusiform rust infection. A new survival function was first developed to estimate future numbers of trees in stands with various proportions of trees infected by fusiform rust. The input parameters needed to predict future stocking, up to and including age 20 of unthinned stands of planted slash pine, are the number of living trees per acre and the percentage of those trees with fusiform rust infection, both at age 5. The original survival model developed for essentially pest-free stands had number of trees planted, stand age, and site index as input parameters. Nance et al. (1983) found the previously developed Weibull diameter distribution model acceptable for translating future stocking into volumes per acre for either rust-infected stands or for healthy stands. Site index and stand age are the variables needed for this translation. A yield table produced from computer outputs shows the expected yields of stands with fusiform rust (Table 1). Impact of rust can be estimated from this table. For example, a stand with 400 trees per acre, a site index of 80, and no rust-infected stems at age 5 has an estimated yield of 3119 ft^3 per acre at age 20. The anticipated yield at age 20 of the same stand with 40 percent stem infection at age 5 is 2210 ft^3 per acre. At age 20, the total impact of rust, excluding degrade, is 909 ft^3 per acre (3119-2210).

Several factors facilitated the development of the fusiform rust model. First was the specific biology of fusiform rust. Most of the potentially lethal rust infections to age 20 were attributable to stem infections that developed by age 5. Distribution of infected trees tended to be random instead of clustered, and most of the effects of rust on yield appeared to be caused by mortality rather than growth reductions in surviving trees. In addition, mortality unrelated to rust was relatively minor in most plots, even to age 20. Another important asset was a group of large data sets from periodic monitoring of both rust and tree growth, in some plots through age 20. Finally, biologists and modelers were willing to participate in model building and evaluation. This willingness also contributed to the development of models for dwarf mistletoe in the West.

TABLE 1. Effects of site index (base age 25), establishment density at age 5, and percentage of stems infected with fusiform rust at age 5 on predicted densities and inside bark volumes at ages 15 and 20 (from Nance et al., 1983).

Established Stand at age 5		Projected plantation age							
		15				20			
No. trees	Rust	No. trees	Site Index 40	60	80	No. trees	Site Index 40	60	80
/acre	%	/acre	----ft³/acre----			/acre	----ft³/acre----		
	0	344	329	1064	2165	319	570	1639	3119
	20	293	323	994	1986	251	516	1449	2715
400	40	239	311	902	1758	185	462	1217	2210
	60	179	275	777	1436	120	375	908	1670
	80	109	232	585	1076	57	249	569	967
	0	675	323	1380	3056	621	689	2252	4358
	20	576	328	1335	2866	489	651	2000	3870
800	40	469	338	1232	2590	359	589	1732	3339
	60	351	334	1072	2178	233	498	1379	2586
	80	214	279	863	1645	111	358	884	1547
	0	1003	295	1462	3497	917	769	2605	5240
	20	855	310	1438	3339	722	715	2362	4682
1200	40	697	321	1392	3100	531	670	2090	3965
	60	522	335	1297	2740	344	584	1702	3264
	80	318	326	1029	2083	164	431	1102	2054

Although growth and yield models like those developed for dwarf mistletoe and fusiform rust are steps in the right direction, it is questionable whether they are sufficiently reliable for judging impacts for specified combinations of conditions (rust levels, densities, sites, and ages, for example). To test accuracy of the rust model, Nance et al. (1983) compared actual and predicted survivals for 1685 observations representing varying intervals between plot remeasurements. The coefficient of determination (R^2) was extremely high (92 percent), and bias and standard error were low. These results give a user unjustified confidence that the model will be reliable for practical application, however. Even with the high R^2, prediction errors of 30 to 50 percent or more are possible for individual plot survivals. A high R^2 is often guaranteed by the nature of the data. In this case, the range of initial establishment densities was wide, rust incidence in most plots was low, and the change in density that occurred between most remeasurement intervals was small. Changes in density were small because intervals between plot remeasurement were often small. For such situations, initial and remeasurement values are very highly correlated. To illustrate further, consider the following example derived from 94 growth and yield plots in slash pine plantations in Louisiana. This particular subset of data, included by Nance et al. (1983), consisted of tree growth and rust incidence measured at 5-year intervals from age 5 through 20. Number of trees surviving at age 10 (T10) is well expressed as a multiple linear function of number of trees living at age 5 (T5) and percent of T5 with fusiform rust stem infection (S5). For this point-to-point model, R^2 is 82 percent, with 71 percent of the variation expressed by T5 and 11 percent by S5. When the prediction period is

chosen to run from age 5 to age 20, however, the R^2 value decreases to 61 percent, with 26 percent of the explained variation accounted for by T5 and 35 percent by S5.

The rust model may be sufficiently accurate for assessing survival, and perhaps future yield, in some circumstances. For many data combinations, however, the model may not be sufficiently accurate and unbiased for assessing impacts (mortality), or for making biological interpretations. The problem is analogous to the greater difficulty and uncertainty of trying to predict growth in comparison to yield. While the R^2 value for predicting survival (T20) in the preceding example was 82 percent, the R^2 value for predicting mortality (T20-T5 as a function of T5 and S5) was only 38 percent. With such low predictability, it is difficult to be certain about prediction biases for specific data combinations, especially combinations not well represented by the data used to build the model. This problem is associated more with sampling than with modeling. The ultimate test for bias, however, may involve additional sampling to determine how the actual mortality compares with predicted mortality, rather than how well actual survival or yield compares with predicted survival or yield.

CONTROLLED EXPERIMENTS FOR ASSESSING FOREST PEST IMPACTS

Another alternative for assessing forest pest impacts is through controlled experiments in which yields of paired plots with and without pest damage are compared over at least a partial forest rotation. Differential levels of pest activity in these paired plots may be achieved by preventing pest damage, introducing pests into designated areas, or simulating damage in some plots. The presumed advantage of the controlled experiment is that experimental error from important but often unknown variables like seed source and the local environment can be minimized. Although controlled experiments are routine for pests that damage annual agricultural crops (see James 1974, Large 1966, Teng and Krupa 1980), they are rare for pests that damage forests. Most experiments with forest pest problems deal with a small segment of the impact problem such as the short-term effects of defoliation or root rot on growth of individual trees, rather than with rotational yields of entire stands.

There are many rationalizations for avoiding controlled experiments on forest pest impacts. They are labor intensive, take a long time to complete, require considerable land for experimentation, and are high risk in terms of probability of successful completion. To complicate matters, impact assessment has generally been erroneously considered a survey function rather than a research function. In addition, controlled impact experiments are probably not feasible for most forest pests. Feasibility depends on the biology of each specific pest and on whether pest activity can be regulated.

A controlled impact experiment for fusiform rust, initiated by one of us (Froelich) in 1978, was made possible largely by the development of the systemic fungicide Bayleton®. Experimentation also was favored by disease epidemiology--early and random development of rust, plus reasonable certainty that natural infection would occur in designated plots.

There are two phases to this experiment. Phase I was replicated in five consecutive years (1978-1982) on each of three high-hazard sites, using paired plots of fungicide versus no fungicide treatments. The fungicide was applied for five consecutive growing seasons in designated plots (except for 1978, when it was not available). Since fusiform rust infection varies considerably from year to year, even on high-hazard sites, replication in time usually results in a wide range of infection by site. Phase I includes 180 plots of slash or loblolly pine (80 trees per plot planted at 6- by 10-ft spacing). Rust-resistant slash or loblolly pines were planted in some plots to quantify gains in productivity that might be expected by planting such material. An initial stand density equivalent of 726 trees per acre was achieved in all plots by planting two trees 6 inches apart and removing one where both survived by May of the second growing season. This procedure eliminated the confounding effects of planting mortality that often attend controlled experiments.

Although preliminary results of Phase I at age 9 are far from definitive, they expose some strengths, weaknesses, and future expectations of the controlled experimental approach to forest pest impact assessment. Bayleton was not available for first year application (1978) in the 12 plots shown in Figure 1, and therefore only partial rust control was achieved in the protected plot of each pair.

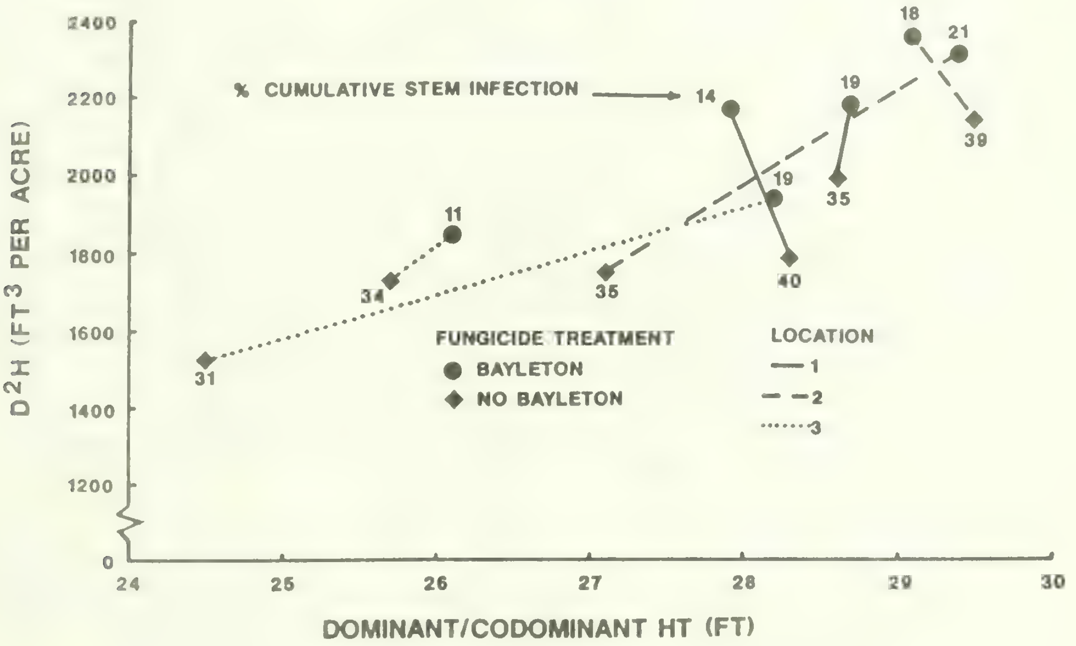

Figure 1. D^2H in ft^3 for 6 of 30 potential pairs of slash pine plots (connected symbols) at age 9, from a fusiform rust impact experiment. Differences between pair members on the vertical scale reflect effects of rust on yield. Differences on the horizontal scale reflect site variations between paired plots.

Nevertheless, rust infection is obviously reducing early yields, which are expressed as D^2H. According to a separate taper study, D^2H is a satisfactory relative measure of actual volume, at least at age 9. The actual volumes of 101 trees were highly correlated with their D^2H volumes, the relationship was close to linear, and unaffected by rust. An unexpected result is the large apparent variation in site quality of some plot pairs, as expressed by average height of dominant and codominant trees. This variation was surprising because plot pairs were adjacent and effort had been made to block the study to minimize site variations between pairs. Many of these differences now appear related to position on slope even though slopes do not exceed 10 percent. In spite of site differences, volume trends of the 12 plots to about age 15--plus the 24 younger pairs of slash pine, and the prospective 30 pairs of loblolly--should provide valuable data for assessing effects of rust over time. It is expected that differences in volume between treated and untreated plots will increase with additional mortality. Due to reduced competition, these losses, however, should be partially compensated for by the increased growth of surviving trees. This problem of compensation may be more adequately addressed by Phase II of the experiment.

Phase II is a rust mortality simulation study attempting to address more fundamental questions about the timing and magnitude of growth compensations in stands with density reduced by rust. We are particularly interested in compensation by age 15, when foresters often thin plantations to meet management objectives. Phase II is being conducted on two low-rust-hazard sites where growth loss in rust infected trees will not be a confounding variable. Two sites were chosen for study. Each contains 48 80-tree plots of slash or loblolly pine. At each site, half of the plots were planted (replicated) in 1978 and half in 1979. Oldest plots have also completed nine growing seasons as in Phase I. When each set of 24 plots reached age 5, three pairs of loblolly and three of slash were chosen for mortality simulation. Because pairing was based on similarities in tree height, plot pairs are not necessarily adjacent to one another as in Phase I. Rust mortality was simulated by randomly removing 25 or 50 percent of the trees by age 9, leaving equivalents of 544 or 363 trees per acre at age 9. Proportions removed each year mimic mortality noted in a previous study in south Mississippi. The remaining 12 plots of each 24-plot set will represent yields and mortality in fully stocked stands that are free of rust.

The main assumption for Phase II is that rust mortality is reasonably well simulated by a random thinning as implied by results in Nance et al. (1983). The study represents only one of an infinite number of possible simulation scenarios, but should permit meaningful interpretations about timing and magnitude of growth compensations.

At age 9, there is no indication of growth compensations in plots where trees were removed to simulate rust mortality (Figure 2). The yield of plots with 50 percent stocking are about proportional to plots of comparable site with 75 percent stocking, or full stocking of about 700 trees per acre. This result was expected because trees are probably

only beginning to compete for growing space and too little time has elapsed for compensations to occur. If these stands compensate in the future for the simulated mortality, yields will not remain proportional to density, but will increase at greater rates in plots with fewer trees. Compensation also will be indicated by greater average diameters of trees in plots with less density.

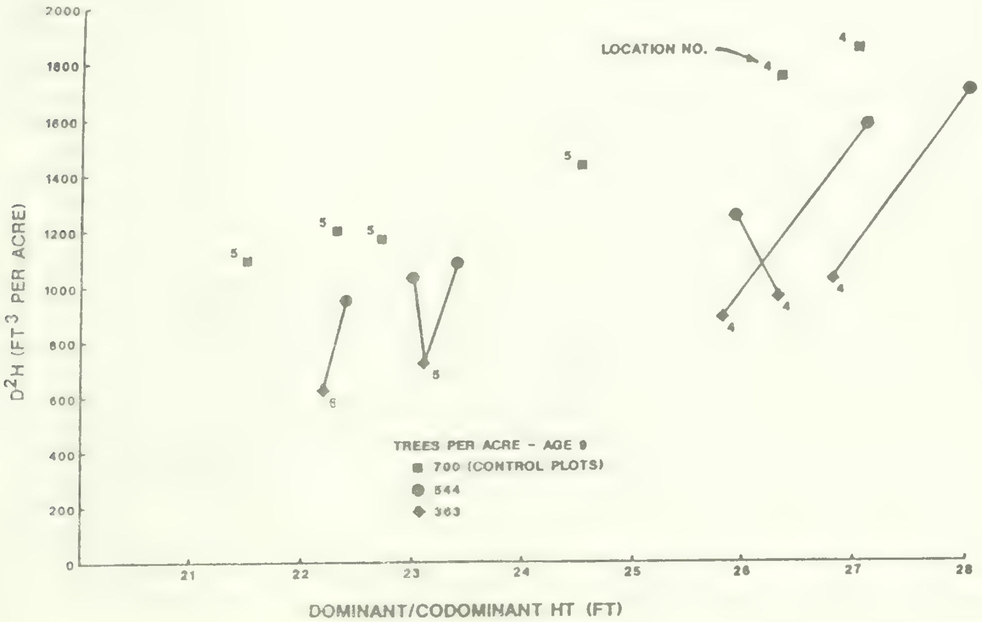

Figure 2.--Effects of simulated fusiform rust mortality on D^2H ft^3 yields of slash pine at age 9. Mortality simulations were accomplished by randomly removing 25 or 50 percent of the trees between the ages of 5 and 9 years in paired plots (connected symbols). Control plots with about 700 trees per acre represent expected yield without rust.

RECOMMENDATIONS FOR FUTURE FOREST PEST IMPACT ASSESSMENT

Although survey data may sometimes be adequate for assessing impacts of pests on forest productivity, growth and yield modeling or controlled impact experiments should be considered when it is apparent that: 1) the pest damage in question is obviously very important, 2) immediate pest damage is likely to be partially compensated for in time by increased growth of residual trees, 3) more precise estimates are needed for cost-effective pest management, and 4) growth and yield modeling or controlled experiments are feasible.

Future growth and yield modeling is likely to emphasize specialized applications like pest impact evaluation or the assessment of genetic gain. Development of such models will require improved data base management, the sharing of important data, and maintenance of long-term

study plots to acquire appropriate data. Possible limitations of models also need to be evaluated. Specialized models may not be sufficiently accurate for assessing yields and impacts for important data combinations, and there may be unacceptable bias in them. Building such models should be considered a dynamic process involving intensive sampling, use of innovative modeling procedures to more accurately mimic stand dynamics, and verification to see how well the model predicts yields and impacts for specific combinations of time, density, site, and pest damage. Point-to-point models may have advantages over models that incorporate time in them. Finally, when feasible, consideration needs to be given to controlled experiments for studying pest impacts. The best, and perhaps only, way to judge a growth and yield model's value for impact assessment is to compare estimates derived from a model with estimates from controlled pest impact experiments.

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MODELING NORTHERN HARDWOOD DIAMETER GROWTH USING WEEKLY CLIMATIC FACTORS IN NORTHERN MICHIGAN[1]

Leslie G. Fuller, David D. Reed, and Michael J. Holmes[2]

ABSTRACT. Existing annual diameter growth models were examined and new equations were developed to estimate seasonal diameter growth of four major hardwood species in northern Michigan. Testing of existing models such as the diameter growth functions used in the STEMS, JABOWA, and FORET models did not produce adequate results for use on northern Michigan hardwoods. Stand, tree, climatic, and soil variables were examined to determine their relationship with cumulative seasonal diameter growth. Certain easily measured stand and soil variables were found to have a relationship with diameter growth and were chosen for model formulation and analysis. A nonlinear equation was developed which estimated annual diameter growth for the species in this study. The annual growth was then scaled with a seasonal ambient multiplier utilizing air temperature degree days to predict diameter increment through the growing season. The multiplier performed very well when tested with validation data from the first growing season and data from a second growing season on the same site. There were no differences in the coefficients of the seasonal multiplier when estimated separately for each growing season. Current efforts are concentrating on improving the performance of the model component which estimates total annual growth by incorporating individual tree competition indices and annual climatic variables into the model.

INTRODUCTION

Environmental conditions can dramatically affect a tree's growth and survival. In this study climate and site variables were examined to determine their relationship to seasonal tree diameter growth for four hardwood species in northern Michigan. Environmental factors examined included air temperature, precipitation, solar radiation, soil moisture, soil temperature, and soil nutrient levels. Stand characteristics measured included basal area, trees per hectare, and crown competition factor along with an individual tree's diameter and height. The objective was to develop a model which could explain differences in both total amount and the seasonal pattern of diameter growth between two sites and across a number of years.

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METHODS AND MATERIALS

SITE DESCRIPTION

The two study sites are located in the Central Upper Peninsula of Michigan. Site one is in Iron County about 8 km south of Crystal Falls at approximately 46°10' N latitude and 88°30' W longitude. Site two is in the southwestern part of Marquette county about 16 km south of Republic at approximately 46°20' N latitude and 88°10' W longitude. Both sites were 30 x 105 meters in size for a total of approximately .315 hectares of forested land. Both have relatively undisturbed second growth northern hardwood vegetation consisting principally of red maple (*Acer rubrum*) and northern red oak (*Quercus rubra*), with minor components of quaking aspen (*Populus tremuloides*), big tooth aspen (*Populus grandidentata*) and paper birch (*Betula papyrifera*). The site is characterized as the Acer-Quercus-Vaccinium habitat type (Coffman *et al.*, 1983).

The principal species mentioned above comprise nearly 100 percent of the overstory on both sites. These trees occupy a wide range of height and diameter classes across all species. Total heights range from 8.8 meters for a red maple to 25.9 meters for a northern red oak. The diameter at breast height (DBH) covers a wide range with a low of 4 cm for a red maple to a high of 59 cm for an old growth northern red oak. A qualitative classification of crown position also includes the full range of classes from suppressed to dominant for all species in the study.

DATA COLLECTION

Measurement of radial increment was accomplished with a band type dendrometer originally developed by Liming (1957) and modified by Cattelino *et al.* (1986). The dendrometer bands were read to the nearest .0254 cm (.01 in) of circumference at both study sites beginning early enough in the growing season to insure monitoring of diameter growth initiation. Weekly readings continued until growth had slowed considerably (at least 95 percent of total incremental growth had occurred) and over 50 percent of leaf fall had taken place. There were 274 trees banded on site one and 197 trees banded on site two before the 1985 growing season (Table 1). A random subset of the measurements from 25% of the trees were removed for model validation from each site.

Table 1. Summary of trees banded by site.

	SITE 1			SITE 2		
SPECIES	N	AVERAGE DBH(cm)	AVERAGE HGT(m)	N	AVERAGE DBH(cm)	AVERAGE HGT(m)
Northern red oak	175	20.55	22.24	45	22.45	17.62
Paper birch	40	16.47	20.63	8	20.23	19.62
Big tooth aspen	25	22.96	23.51	15	25.01	20.27
Red maple	15	11.97	16.31	129	15.09	16.43
Quaking aspen	19	22.81	24.47	---	-----	-----

The second part of the data collection process for this study involved climate and soil data which may affect plant growth processes. Each of the study sites was equipped with a Handar 540A[1/] data collection platform located in a cleared area adjacent to the site. The main plot with the data collection platform contains the precipitation, air temperature, relative humidity, solar radiation, soil temperature, and soil moisture sensors; 30m X 35m subplots contain air temperature, soil temperature at 5 and 10 cm depth and soil moisture sensors at 5 and 10 cm. Data are retrieved eight times daily via NOAA satellite transmissions at three hour intervals. Sensor data are queried every 30 minutes during the three hour period and computed into a mean value by the platform microprocessor. Precipitation data are logged once each three hour period. The daily climatological and soil data are summarized into weekly averages for analysis. These field recorded climatological and soil variables can then be processed to get other information such as maximum and minimum air temperature, growing degree days, and total precipitation.

GROWTH MODEL DEVELOPMENT

EXISTING GROWTH MODEL COMPARISONS

An initial step in this study was to evaluate existing growth models to determine whether they could provide adequate estimates of annual diameter growth on the study sites. Three models were tested using the data from sites one and two. The first diameter growth model tested was a general model developed in the Lake States Region of the United States using simple stand parameters as predictors (U.S.D.A., 1979). This model overestimated growth for all species on both sites. The predictions by this model on the study sites were no better than using average growth as a predictor of annual increment.

Two other annual growth models were also examined (JABOWA (Botkin et al. 1972) and FORET (Shugart and West 1976)). These used a technique which first predicted the ecological potential annual diameter growth and then modified the potential growth with operational environment factors. This ecological approach used environmental factors such as growing degree day heat sum (the annual sum of daily departures of temperature above a 4.4°C base temperature), available light based on the "shading leaf area" of the trees which were taller than the tree in question, and a measure of competition based on basal area of the stand. Shugart (1982) examined other factors such as nutrient availability, evapotranspiration, and photosynthesis light-response curves to develop dynamic gap successional models. In both studies yearly growth was tracked through time with subsequent ingrowth, mortality, and site factors to produce a successional model. The annual diameter growth functions from these models did not predict well on the study sites and, again, were no better than using the mean as an estimate of growth.

1/ Equipment models, brand names, and trademarks are given for the reader's information. No recommendation or endorsement is intended or implied.

In this study we examined the relationship between growth and the ambient and stand factors discussed previously using an approach simil-iar to that developed by Botkin et al. (1972). The advantage of this approach was to use a basic diameter growth model first, and then develop methods to scale that growth dependent on the climatic or soil factors. The variables which proved most influential were incorporated into growth models estimating the seasonal radial growth for the four species.

CORRELATION ANALYSIS

Relationships between growth and environmental factors were examined. Correlation matrices and plots of dependent (diameter growth) versus independent (ambient, soil, and stand factors) variables were used to determine which factors should be used in further analysis. The factors that showed the greatest correlation were cumulative air temperature degree days, total precipitation, and soil temperature cumulative degree days for both 5 and 10 cm depths. In the analysis of these variables, air temperature degree days and soil temperature degree days were highly correlated with each other. Only one would be used in the analysis because the other would not significantly increase predictive ability. Of the tree and stand variables examined, growth was most highly associated with diameter, height, and crown width. Crown width was calculated as a function of diameter and it was not considered for further analysis.

MODEL DEVELOPMENT

An existing annual diameter growth function was used to develop cumulative diameter growth models. The coefficients were re-estimated using regression techniques for each of the species in this study. The annual growth was then scaled with a seasonal multiplier developed from ambient data specific to this study site. The seasonal growth model took the form:

$$CG_t = (\text{Annual Growth})(\text{Seasonal Multiplier}_t) = (AG)(SM_t) \quad [1]$$

where CG_t is the cumulative growth over the season to time t. Annual growth (AG) represents total growth expected over the season, and the seasonal multiplier (SM_t) estimates the proportion of annual growth to time t.

ANNUAL GROWTH

An existing diameter growth function was examined as a predictor of annual diameter growth. The functional form was originally developed by Botkin et al. (1972):

$$AG = \frac{GD\,(1 - DH/D_{max}\,H_{max})}{(274 + 3b_2D - 4b_3D^2)} \quad [2]$$

where AG equals annual diameter growth, G equals a species specific growth constant, H equals tree height, D equals tree diameter, D_{max} equals maximum tree diameter, H_{max} equals maximum tree height, and b_2 and b_3 are estimated coefficients. The function's original coefficients and values shown by Botkin _et al._ were used as starting values in a regression routine to fit coefficients specific to the species in this study. Values for D_{max} and H_{max} given by Botkin _et al._ (1972) were used directly and not re-estimated. Other model forms, including a linear model, were examined but did not yield better results.

SEASONAL AMBIENT MULTIPLIER

The objective of this study was not only to predict annual tree diameter growth but to be able to track that growth throughout the growing season using stand, tree, and ambient variables. A seasonal ambient multiplier which scaled the total annual growth throughout the growing season was developed. An approach similiar to that of Botkin _et al._ (1972) was used. Potential annual growth was scaled by environmental modifiers to adjust estimated annual growth for local climatic and site conditions.

The multiplier was applied to the annual growth function [2]. The form of the multiplier was based on the Weibull cumulative density function (Bailey and Dell, 1973):

$$SM_t = 1 - EXP(-(X_t/b)^c) \qquad [3]$$

where SM_t equals the seasonal multiplier to time t, X_t equals a climatic variable, and b and c are estimated parameters. This function distributes the annual growth over the growing season. Cumulative air temperature degree days (4.4°C basis) was used as the variable in the seasonal multipler. Other ambient variables including precipitation, solar radiation, and humidity were considered. However, cumulative air temperature degree days was the dominant variable controlling growth on the study sites. The values of b and c were estimated for each species using regression techniques (Table 2).

Table 2. Nonlinear coefficients refitted to an annual growth function and an ambient multiplier to predict diameter growth to time t during the growing season.

	Sample[a/] Size	G	b_2	b_3	D_{max}	H_{max}	b	c	PVE[c/]
NRO[b/]	2760	1.3428	-3.5860	-.0432	244	4877	716.45	1.398	.4812
PB	826	0.5197	-5.9591	-.0769	46	1830	754.85	2.264	.5968
ASPEN	1072	0.3132	-6.8175	-.1022	152	3200	740.48	2.378	.6484
RM	1725	1.9290	-3.4174	-.0642	152	3660	847.77	2.303	.4439

a/ weekly observations * number of trees
b/ NRO = Northern red oak
PB = Paper birch
RM = red maple
c/ proportion of variation explained

TESTING OF EQUATIONS

These equations were then tested against actual cumulative diameter growth values from the validation data set. The results of the testing for the growth function with the seasonal multiplier are given in Table 3. Average residual (observed - predicted) is listed in the table along with the proportion of variation explained (PVE). When using equations 3 and 4, the models predicted growth well except in the case of paper birch. This discrepancy can be explained by the structure of the validation sample. For both sites the sample size is relatively small for paper birch. A number of these trees did not exhibit any growth over the season, hence creating a situation which affected the model's performance for that species. For the other species, the model performed better on the site which contained the majority of the species sample. This included northern red oak and aspen on site 1, and red maple on site 2.

Table 3. Test statistics for the diameter growth model.

	EQUATION 2 & 3		ACTUAL GROWTH & EQUATION 3	
	AVERAGE RESIDUAL(%)	PVE[a/]	AVERAGE RESIDUAL(%)	PVE
ALL DATA				
Red oak	0.9	.6170	2.2	.9772
Paper birch	-32.0	-.0401	-2.1	.9659
Aspen	12.0	.5420	-1.5	.9708
Red maple	-5.4	.4796	0.2	.9780
SITE 1				
Red oak	-1.5	.6698	1.6	.9775
Paper birch	-52.3	-.0782	-0.1	.9613
Aspen	4.6	.8630	-2.5	.9567
Red maple	40.3	.1699	3.5	.9662
SITE 2				
Red oak	14.5	.2317	5.9	.9729
Paper birch	29.8	-.0235	-3.8	.9784
Aspen	26.4	.0897	0.4	.9833
Red maple	-9.6	.4920	-0.1	.9785

a/ proportion of variation explained

The seasonal multiplier was also tested by applying the multiplier to the actual yearly diameter growth and comparing this with the actual values in the validation data (Table 3). As is shown by the high PVE values for all species, the multiplier performed very well in its ability to scale yearly growth to seasonal values. This also indicated that the reason for any inadequacies in the complete equation lie in the poor predicitve ability of the annual diameter growth function using stand and tree factors, not the seasonal ambient multiplier.

Further evaluation of the seasonal ambient multiplier gives insight into how it reacts based on the species it is being used for. Figure 1 shows the seasonal pattern created by species for air temperature degree days from 100 to 1800. The intolerant species of paper birch and aspen (big

tooth and quaking) show a steep pattern which takes full advantage of the degree days available during the most active period of the growing season. The more tolerant species of northern red oak and red maple show a flatter pattern which continues to increase until the upper limit of air temperature degree days near the end of the growing season.

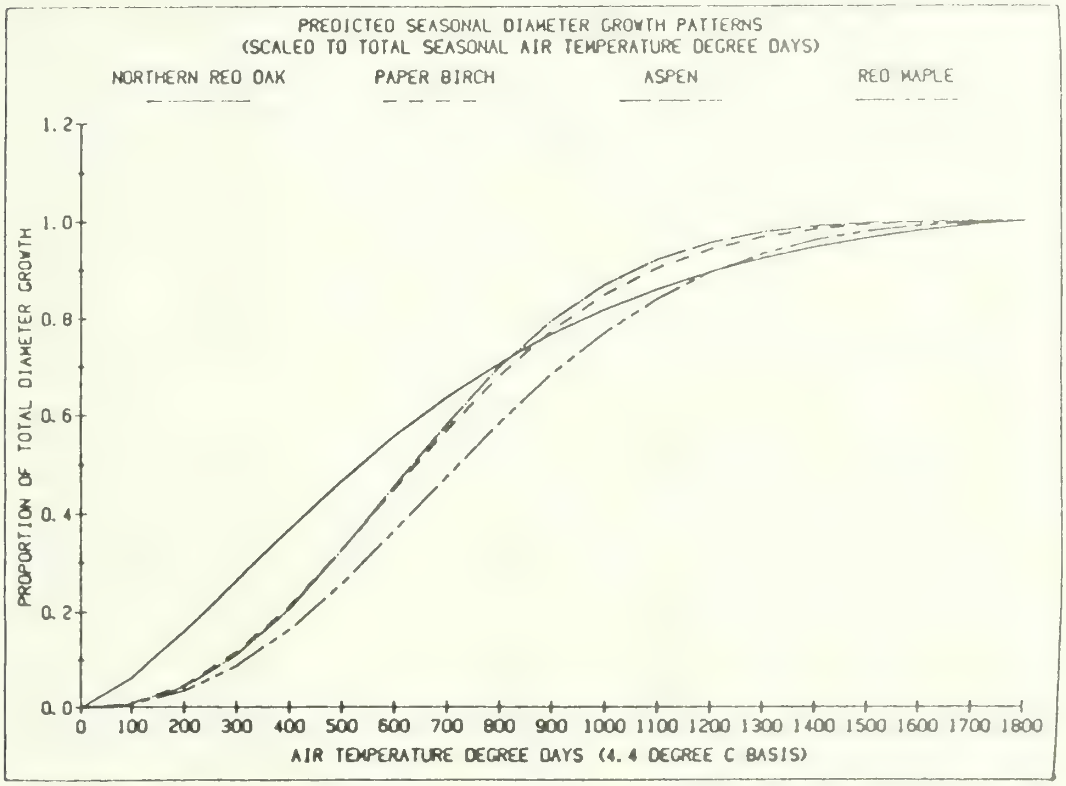

Figure 1. Seasonal pattern by species.

The coefficients of the seasonal modifier estimated for the 1986 growing season were not significantly different (α = .05) than those estimated for 1985. There were differences in the annual diameter growth model coefficients. Moreover, the additional testing of other ambient variables such as soil moisture did not effectivly change the seasonal multiplier or its predictive power for 1986. Significant correlations ($\alpha \leqslant$ .05) were found between the growth model residuals and variables representing competition levels such as "area potentially available". Current work is focusing on incorporating competition variables into the annual growth function. Also, the year to year variation was explained, in an analysis of covariace, by annual soil degree days (4.4^{o} C basis) at 5 cm for northern red oak and aspen, by annual air temperature for paper birch, and by May soil temperature and June soil moisture (5 cm) for red maple. Site variation was also explained, with an analysis of covariance, by initial diameter and plot water holding capacity for paper birch, and by initial diameter and plot basal area (m^2/ha) for red maple. For red maple both year and site variation are partially explained by June potassium concentrations (ppm) in the soil. Current work on incorporating variables explaining site to site and year to year variation is also proceeding.

SUMMARY AND CONCLUSIONS

Northern hardwood diameter growth pattern over the length of one growing season was estimated using a combination of stand, tree, and ambient variables as predictors. The approach, which estimated the seasonal growth more precisely than any other in this study, was the refitting of nonlinear coefficients to an already existing annual growth function and the scaling of that function with a seasonal ambient modifier. This annual growth function and seasonal modifier performed better with the study validation data than any other existing or newly developed equation examined. Current work is focusing on improving the annual growth funtion by incorporating competition indices and annual climatic variables into the model.

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A METHODOLOGY TO INVESTIGATE RELATIONSHIPS BETWEEN LONG-TERM TREE-GROWTH PATTERNS AND ANTHROPOGENIC POLLUTANTS

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ABSTRACT. High quality data of pollutant deposition is lacking. Thus, surrogate variables must be used in place of pollutant measurements. Surrogate variables should be highly related with pollutant deposition and must not affect tree growth. The use of surrogate variables reduces confidence in our inferences to an unknown degree. Several measures of tree or stand growth may be considered as a response variable. As height growth of dominant and codominant trees is insensitive to many factors that affect other components of growth and may be interpreted as potential productivity, it should be the preferred measure of tree growth. A methodology is developed for use with a large stem analysis data base. Problems inherent in this research restrict inferences to be regarded as objectively-developed theories. Real tests of hypotheses await long-term designed experiments.

INTRODUCTION

Forest declines have been observed recently in Europe, the eastern United States and the Pacific rim (McLaughlin, 1985; Schutt and Cowling, 1985; Mueller-Dombois, 1986). Natural processes, as affected by climatic trends have been accepted as the cause of the declines in the Pacific rim (Mueller-Dombois, 1986). Strongly-supported theories have not been provided for the decline in southern pine growth (Sheffield et al., 1985). Climate and anthropogenic atmospheric pollutants have been implicated in the declines in central Europe and the northeastern United States (McLaughlin, 1985; Krause et al., 1986). Decline symptoms of acute tree mortality and crown die-back have been preceded by reductions in tree growth (McLaughlin, 1985; Johnson et al., 1984).

Atmospheric pollutants from fossil fuel combustion have increased over the past century (McLaughlin, 1985; Burgess, 1984). Deposition of these substances may have a profound effect on the processes of natural ecosystems (Burgess, 1984; Smith, 1984). Thus, it is reasonable to investigate the potential relationships between long-term tree-growth patterns and anthropogenic atmospheric pollutants. We attempt to develop a framework that is suitable to study such relationships and we discuss problems that are specific to this topic.

IDENTIFICATION AS A MODELING PROBLEM

Given a multi-variable data set, statistical modeling is often the best

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way to synthesize information regarding the relationship between a response variable and several independent variables. Alternatives to modeling include graphical techniques that are often informative, but necessarily subjective. Raynal and his coworkers (Raynal and LeBlanc, 1985; LeBlanc et al., 1987) give results for a few "typical" trees and thus their conclusion of no unexpected growth decline is based on anectdotal evidence rather than a formal data analysis. Other studies plot average growth based on many trees (Hornbeck and Smith, 1985; Johnson et al., 1984). Such graphs exhibit overall growth-trends. As different individuals may be responding to different factors, the cause of the growth trends is obscured. Statistical modeling methodology may give the impression of quantifying the effects of a given anthropogenic factor, or of testing a hypothesis regarding some effect. However, problems that are discussed in succeeding sections indicate that such statements need to be qualified.

CHOOSING INDEPENDENT VARIABLES

Records of acidic deposition and oxidant concentrations are poor or absent. High quality precipitation chemistry data extend back only 10-15 years (Pinkerton, 1984). Thus, reconstruction of air pollutant patterns over a longer time-frame is problematic. The network of collecting stations is sparse and none may be near a given study area. Furthermore, local variation in pollutant deposition may be large, particularly in mountainous regions.

Direct measurement of deposition may be replaced by surrogate, or proxy variables. Surrogate variables should possess two properties: 1) strong relationship with pollutant deposition; 2) does not affect the response. If the "variable of interest" is one specific component of atmospheric pollution, then the surrogate should be highly correlated with only that component. If the surrogate is correlated with several components of atmospheric pollution, inferences regarding any single component are abrogated. Thus, the use of surrogates often forces us to restrict inferences to a suite of regionally transported atmospheric pollutants and we lose resolution regarding any single component. This characteristic disallows determination of a dose-response effect. A dose-response effect may only be determined from a carefully-designed study (Landau et al., 1985; Anderson et al., 1985; but see Krupa and Kickert, 1987). The surrogate must not affect the response or some effect may be presumptuously attributed to atmospheric pollutants.

The quality of a surrogate is determined by how well the two criteria are satisfied. Below, we discuss several potential surrogates for atmospheric pollutants.

1) Regional fuel consumption. Regional fuel consumption is indicative of emissions of regionally-transported atmospheric pollutants. The quality of fuel is not constant, and thus consumption may not be linearly related to emissions.

2) Modeled emissions. Estimated emissions may be used when a suitable model and the required data are available. However, the model may not be applicable to, and the data may not be available for, the entire time-

frame of interest. Emissions don't necessarily reflect deposition, which is affected by physiography, weather and vegetation.

3) Modeled deposition or concentration. Deposition models are generally more data-intensive than emission models and may be limited by availabilty of suitable data and models that are calibrated for the desired conditions. Simple models may consist of maps with isopleths for a given pollutant. Deposition or concentration does not represent the "effective dose" absorbed by a plant (Krupa and Kickert, 1987).

4) Geographic regions. There are obvious gradients of pollutant concentration from urban and industrial areas to rural and wildland areas. Thus, at least on a given scale, geographic regions may show a high correlation with the variable of interest. However, although geographic regions, by themselves, do not affect tree growth, other variables which do affect tree growth vary concomitantly with geographic regions. Climate, soil parent material, and land-use history are examples of factors that differ across geographic regions and that may have large effects on tree growth. Although a model could be used to remove much of the effect of these variables, part of the effect of pollutants could be removed or an effect of some neglected variable may be attributed to atmospheric pollutants.

5) Elevation X aspect classes. It is known that, in mountainous regions, higher elevations receive more atmospheric deposition and oxidant impact than lower elevations and that aspect determines whether prevailing winds cause more or less deposition. This surrogate is strongly related to rainfall and soil depth, two factors that affect tree growth. Thus, this variable does not satisfy the second criterion for a suitable surrogate.

6) Time-before-present. As atmospheric pollutant concentrations have varied directionally over time, time-before-present is related to atmospheric pollutants. Time-before-present, by itself, does not affect tree growth, after adjusting for age. However, climate does vary over time and climate does affect tree growth. Thus, before making any inferences regarding atmospheric pollutants, adjustments must be made for climate and any other factors, such as stand structure, that vary over time and affect tree growth. The age of the individual trees must vary or time-before-present will be perfectly collinear with age.

7) Inversion days. Inversion days indicate the potential for high ozone levels. As inversion days are determined by climate and not emissions of oxidants, it is problematic to attribute a mechanism of cause and effect to any observed growth decline related to inversion days. Inversion days will likely be poorly correlated with most other potential variables and thus may have a high likelihood of being included in a model.

Other potential surrogates may exist. For example, Johnson et al. (1984) used streamflow pH as a surrogate for deposition of sulfate. As atmospheric inputs are modified by the characteristics of the watershed, streamflow pH among several watersheds is not indicative of inputs to a given watershed.

Regardless of the quality of the surrogate, our confidence in inferences relating anthropogenic pollutants to tree-growth patterns is reduced to an unknown degree. That is, inferences are only valid regarding the relationship between tree growth patterns and the surrogate. If our inferences are based on, say, whether a confidence interval for a parameter includes zero, the significance of the true variable of interest will likely be considerably different from the nominal confidence interval. Thus, any "inferences" should be regarded as reasonable, objectively-developed theories, rather than a result of a test of an hypothesis. Such hypothesis tests await the result of long-term designed experiments (Landau et al., 1985; Anderson et al., 1985).

CHOOSING A RESPONSE VARIABLE

Numerous indices or measurements of components of individual-tree or whole-stand growth could be considered as a response variable. Most often diameter growth at a specified height above ground has been used (Johnson et al., 1984; Puckett, 1982; Cook, Johnson and Blasing, 1987). Raynal and LeBlanc (1985) have considered various types of growth-sequences that may be derived from stem analysis (Duff and Nolan, 1953).

There are numerous factors that may potentially affect tree growth. Many of these factors may be highly collinear. In the presence of collinearity, model parameters are unstable and are estimated with high variability (Draper and Smith, 1981). Inferences based on such parameters may be misleading. We may minimize this critical problem by chosing a response variable known to be insensitive to many factors. If the response variable does not have this characteristic, there is a possibility of attributing some affect to anthropogenic pollutants when it does not exist, or attributing the effect of pollutants to some other variable (Anderson et al., 1985). Thus the theories we generate would be based on evidence that is much less compelling.

Secondary qualities the response variable should possess are: 1) should be related to stand-level productivity; 2) there should be a large body of literature regarding modeling methodology; 3) should be "real" rather than derived. Any inferences regarding the effect of anthropogenic pollutants will carry more importance if they are related to productivity. A large body of past research will reduce the likelihood of attributing some idiosyncracy of model form to the effect of pollutants. Highly derived variables may hinder our interpretation of any effect of that variable. Some derived indices may introduce a systematic bias that could be attributed to anthropogenic pollutants (Landau et al., 1985).

Height growth of dominant and codominant trees (or site index) is the variable that best satisfies these criteria. The literature regarding the theory and modeling of site index and height growth is abundant. Stage (1963) and Monserud (1984) have shown that the site index concept may be extended to stands that are not strictly even-aged. Height growth of site index trees is insensitive to broad ranges of stand density and other stand-level characteristics (Lanner,1985). Site index is interpreted as potential productivity and thus any inferences regarding site index will have more far-reaching importance than, say,

diameter growth. Although other dependent variables may be considered, we believe that any alternatives should be used in addition to, rather than in place of, height growth of site index trees. The potential application of the site index concept has been identified (Loucks, 1984), although tree height growth data have not yet been used.

MODEL FORM AND FITTING

This section specifically considers a height-growth model, although the concepts could be applied to other models.

Numerous functional forms have been used for height-growth or site index equations. An individual model form may have certain attributes that limit its potential use for investigating the effects of anthropogenic pollutants. The models predict height based on age, site index and occasionally base age. We will name such a model the base model. A model that is expanded to include variables associated with atmospheric pollutants will be called the expanded model.

A base model should represent the "true" functional relationship for height growth over time. "True" implies that there are no patterns in the residuals. Patterns must be absent when the residuals are plotted against predicted values and independent variables for either the entire data set or a meaningful subset of the data. There will be a pattern in the residuals plotted against age unless the site index model is base-age invariant. Similar patterns could be expected from any self-referencing function (Northway, 1985). Subsequent analyses could attribute such artifacts of model form to anthropogenic pollutants. Similarly, a splined model form could potentially obscure an effect of pollutants by locating a join-point at a phase-shift from "normal" to "affected" growth.

Given an appropriate base model, a suitable procedure must be developed to include variables associated with anthropogenic pollutants. One could attempt to model the residuals of the base model as a function of pollutant-related variables. Such a procedure is unreasonable unless independent variables of the base model and pollutant-related variables are close to orthogonal. In the presence of collinearity, one would give priority to the independent variables of the base model. Instead of questioning whether pollutants are affecting tree growth, the research question would be changed to "Is the base model improved (according to some criterion) by adding pollutant-related variables?" Individual researchers will need to determine whether this is the question they wish to pose and qualify their conclusions appropriately.

Alternatively, the expanded model could be fit directly. If several pollutant-related variables are considered, it is likely that one or more will be "statistically significant" (although not necessarily biologically important). Significance does not infer causality as it may be due to the effect of other factors that may be related to that variable. A parameter estimate will be affected by the presence or absence of other variables in the model. Thus it is erroneous to equate a parameter estimate with a marginal effect of a unit of a given variable, unless the data arise from a controlled design (Landau et al.,

1985; Anderson et al., 1985).

Many base models for forest or tree growth are nonlinear. There is no clear statistical methodology for adding a variable to a nonlinear model when the form of the expanded model is unknown. Generally, however, there are three ways in which a new variable may enter a model. A new variable may enter additively to the base model as some function of that variable and other variables in the model. Alternatively, the new variable may enter multiplicatively as some function that is logically constrained. Finally, the new variable may expand the parameters of the base model to be some function of the new variable. Such conditional values for the parameters of the base model give a Bayesian or, perhaps, random coefficients flavor to the model fitting. A random coefficients-type model may also be appropriate when pollutant-related variables are regional averages and thus do not represent the deposition that any individual received. However, the random coefficients method is only applicable to linear models or nonlinear models where a linear approximation is adequate (Johansen, 1984).

OUTLINE OF A METHODOLOGY

The following methodology is based on the considerations outlined above. We believe it is the most appropriate analysis in the absence of a well-designed study where deposition data are coordinated with tree-growth data. We intend to carry out the analyses on several existing stem analysis data sets from eastern North America. Each data set will be analyzed according to the following outline of procedures.

1) A standard height-growth model will be fit. If patterns exist between residuals and either predicted values or independent variables, the model will be revised or replaced. Presently we are developing a base-age invariant height growth model based on the Richard's function.
2) Long-term growth trends will be determined using an added-variable technique with time-before-present as the added variable. If no long-term growth trends are observed, we will conclude that anthropogenic factors are not having an appreciable effect and analysis of that data set will stop. Time-before-present is a reasonable initial surrogate as stand dynamics do not affect site index for our species. This step amounts to a test of whether there is a long-term trend in tree height growth.
3) Climate is the most obvious cause of possible long-term tree growth trends. Before a growth trend may be attributed to anthropogenic factors, climate must be considered. This is resolved as an added variable problem with the model fit in step one as the base model and climatic variables as the added variables. Step two will then be repeated using the climate-modified model as the base model. This step will test whether long-term growth trends are adequately explained by climatic variables.
4) We will attempt to add variables related to anthropogenic atmospheric pollutants to the climate-modified model. Long-term data for pollutant deposition are lacking. Thus surrogate variables will be used. If any of the surrogate variables are important in explaining the long-term growth trend, theories will be <u>generated</u> regarding the

mechanisms of the observed effect.

This methodology is somewhat conservative in attributing a growth pattern to anthropogenic pollutants. We are giving priority to age and climate over pollutants. This is only justified when the base model is parsimonious (as site index models are) and when the data base contains individuals across a relatively broad range of ages.

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TREE-RING ANALYSIS OF A 500-YEAR OLD HEMLOCK IN CENTRAL PENNSYLVANIA

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ABSTRACT. A single 500-year old hemlock from central Pennsylvania is used in a limited dendrochronological study. Ninety-four years of the 385-year ring-width series were used to model radial growth using lagged climatic and growth variables. Results showed the hemlock to be a climatically sensitive specimen. A linear model with an $R^2 = 0.64$ is presented.

INTRODUCTION

Central Pennsylvania is situated in the Ridge and Valley section of what was formerly known as the Oak-Chestnut Forest region (Braun, 1950). American chestnut is no longer an important component of this forest type in Central Pennsylvania due to its demise in the early part of this century from the chestnut blight (*Endothia parasitica*). With the loss of this important species component the forests of this region are now more commonly grouped into the oak-hickory forest type and are, with few exceptions, secondary forests. A number of distinct communities exist within this forest type in which red oak, white oak, chestnut oak and scarlet oak occur as dominant species (Braun, 1950). Powell and Considine (1982) recognize nine oak-hickory types within which the oaks make up approximately 40 percent of the growing stock volume.

Nestled in many of the ravines and higher mountain valleys of the Ridge and Valley region occur pure hemlock or hemlock-white pine communities often with abundant Rhododendron occuring in the understory (Braun, 1950). Most of these stands are also secondary in nature with a few exceptions of primary stands still in existence. One such primary stand is located in the Alan Seeger State Forest Monument. This stand is composed of two primary forest communities as differentiated by Braun (1950). The hemlock forest type is composed most notably of eastern hemlock, white pine, white oak, red maple and tulip poplar in the overstory with abundant Rhododendron in the understory. The type is located in the lower mesic flats of the ravine with a more dominant oak-pine type occupying the upper parts of the ravine. It is in this lower flat hemlock community that Old Henry, which blew down in February 1981, and other remnant hemlocks thought to be as much as 500 years old still exist.

The natural death and subsequent windfall of Old Henry presented the interesting prospect of using this repository of information in a limited dendrochronological study. A cross-section of Old Henry cut shortly after it fell, at a height of about 53 feet (the approximate height of the beginning of sound wood in the main stem), was used for this study.

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The emphasis in this study is on the modeling of radial growth of Old Henry through the use of climatic variables. As such, this is a modified dendroclimatological study in that the intent was only to model growth -- not to reconstruct past climate from tree rings (Fritts, 1976). The sample size of one tree (Old Henry) precluded such an analysis from the beginning.

A large body of the methodology of tree ring analysis has grown out of the successful application of dendrochronology in the semiarid parts of the southwestern United States (Fritts, 1976). In this section of the U.S. certain species may be highly sensitive to environmental factors such as precipitation on sites where these factors may be limiting with respect to tree growth. However, in the eastern deciduous forests, the selection of sites (hydric, mesic and xeric sites are often differentiated in tree-ring studies (Fritts, 1975; Phipps, 1982)) and species which will show climatically sensitive ring-width chronologies may be confounded with such factors as crown competition in closed-canopy woodlands and shade tolerance. Phipps (1982) notes that ring-width data from eastern deciduous forests are generally not expected to be as sensitive to climatic data as are those from species of the semiarid portions of the southwest. In the eastern deciduous forests the degree to which environmental factors of a site limit growth is deemed more important by Phipps in the selection of site than whether the site itself is hydric or xeric.

Species and individual tree selection are equally as important as site selection. Cook (1982) lists a number of species indigenous to the eastern U.S. which are likely to be or have been found useful in dendroclimatic studies. Among these he notes that eastern hemlock growing on hummocks in ravine habitats may be a climatically sensitive species and posseses the desirable characteristic of longevity necessary for dendroclimatic modeling. Lyon (1935, 1936) studying virgin hemlock in New Hampshire and Vermont also showed hemlock to be a climatically sensitive species, correlating favorable and unfavorable growth with periods of drought or adequate precipitation respectively.

In selecting individual trees of any species it is obviously important to select old (not necessarily large in girth) trees so that a long enough growth chronology may be established. Thus, it is important to consider all three factors (site, species and individual tree) in developing ring-width chronologies which can be correlated with climate, giving preference to shade tolerant overstory trees for climatic sensitivity (Phipps,1982).

Old Henry was found on an upper mountain valley site in close proximity to a year-round stream with very little, if any, crown competition, at least in recent history. The exact age of Old Henry is unknown due to the decayed lower section of the tree, however, there were 385 growth rings at approximately 53 feet in height. The decay also prevented the exact measurement of diameter at breast height (dbh) though an approximate measurement of 52 inches was taken. Total height was never measured but an extant neighboring hemlock, not quite the size of Old Henry, measures 47.7 inches dbh and 113 feet in height. Thus, the final important criterion of longevity is satisfied in Old Henry. This suggests that Old Henry, being of shade tolerant lineage in a dominant open-grown crown position, meets the above general requirements set forth by Phipps and Cook to be at least

moderately sensitive in ring-width chronology to climate. It was viewed as a good specimen on which to try dendroclimatic modeling techniques.

DATA COLLECTION AND ANALYSIS

I. Old Henry Tree-Ring Series

Any dendrochronological study begins first with securing an adequate number of samples which should be collected, prepared, measured and crossdated utilizing standard techniques such as those set forth by Fritts (1976). This study is in violation of those standard techniques because an adequate sample was not secured (Old Henry is our only data) and collection of the cross-section on which ring width measurements were taken was done at an arbitrary 53 foot mark on the stem rather than at a more standard height. Actual ring widths were measured using an instrument which could measure to the nearest hundredth of a milimeter (mm). The resulting 385 year ring-width series and some elementary statistics of the series are presented in Figure 1a and Table 1a respectively.

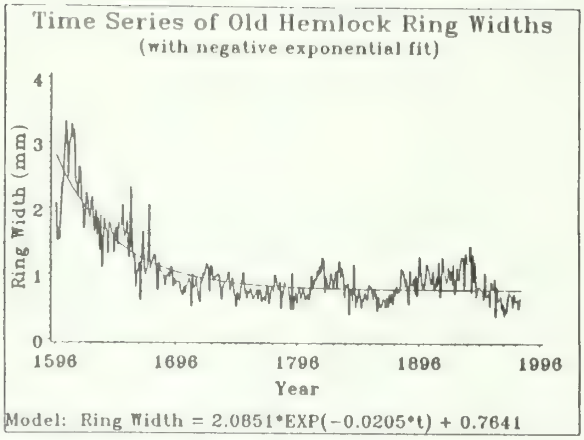
Table 1. Elementary statistics for Old Henry (a) ring-width series (b) and (c) ring-width index series

Statistic:	(1597 to 1981) (a)	(1597 to 1981) (b)	(1887 to 1981) (c)
N :	385	385	94
Mean :	1.02 mm	1.00	1.11
Standard Dev. :	0.52 mm	0.25	0.31
Variance :	0.27	0.06	0.10
Minimum :	0.36 mm	0.47	0.47
Maximum :	3.33 mm	1.87	1.87
Mean Sensitivity[1] :	0.19	0.19	0.23

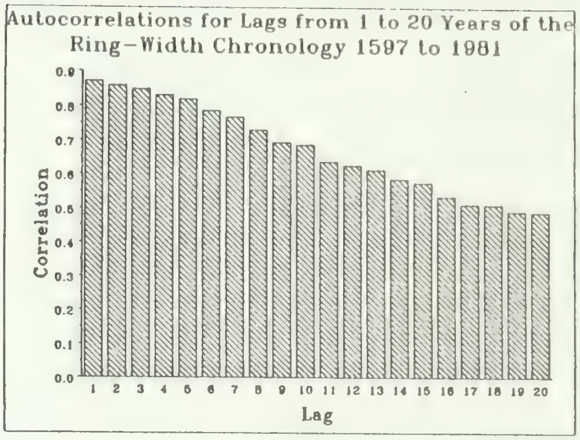
[1]The mean sensitivity was developed by A. E. Douglass for tree-ring data and is defined by Douglass (Fritts, 1976) as the "mean percentage change from each measured yearly ring value to the next" and ranges from a value zero (indicating no change) to two.

The low value of mean sensitivity for this series reflects the absence of a significant amount of high-frequency variance. High-frequency variance is an indication of cycles of approximately eight years or less in the data which may be at least partially attributable to year-to-year ring-width variation and short-term climatic variations (Fritts, 1976).

Figure 1b presents a histogram of the autocorrelation for lags of one to twenty years. The histogram shows a slow, approximately linear decline in autocorrelation implying that current ring-width is influenced by a number of years of past growth. This histogram indicates a large amount of low-frequency variance which may be defined as long-term (over eight years) variations in ring widths and may be due in part to long-term variations in climate (Fritts, 1976). It is this low-frequency variance that is important in relating growth to climate.



(a)



(b)

Figure 1. Time series of Old Henry ring widths (a) and autocorrelation function (b).

The statistics calculated thus far include the effect of the declining growth trend common to many conifers (Figure 1a). This trend must be removed from the data to make the series stationary. A stationary series is one with constant mean and variance over time. Note in Figure 1a that both the mean and variance of the Old Henry series decreases over time. Stationarity is accomplished through standardization of the series and results in a series clean of the effects of the biological growth trend. The model used to fit the trend was proposed by Fritts (1976):

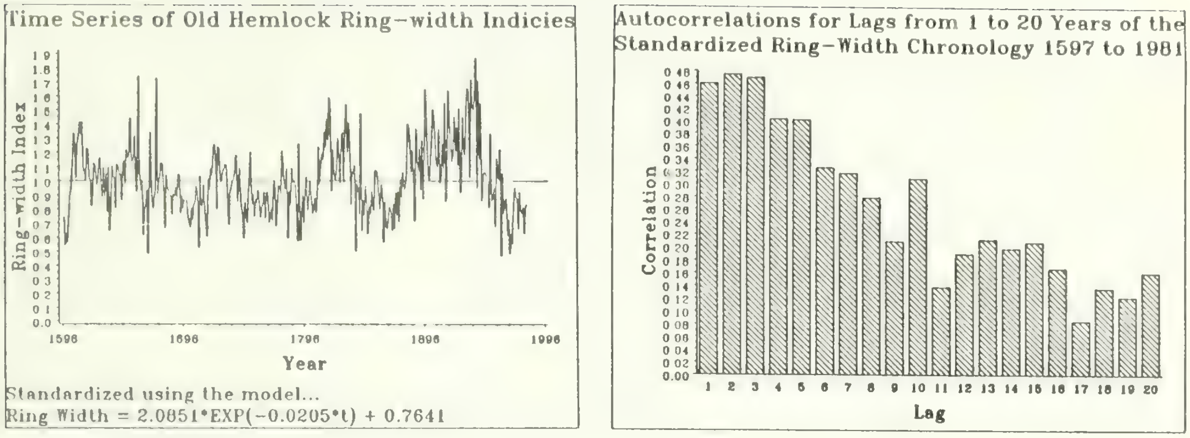
$$E(Y_t) = \alpha * EXP(\beta t) + \delta. \tag{1}$$

In this model Y_t is the ring width in mm, t denotes time and α, β and δ are regression coefficients estimated using PROC NLIN in SAS (SAS, 1985). The fitted model is shown in Figure 1a. Standardization of the series was then accomplished by dividing the original ring widths by those predicted from model (1). The standardized ring-width series is plotted in Figure 2a and elementary statistics are presented in Table 1b. Note that standardization using model (1) rather than some higher order polynomial model which would "fit" the data more completely leaves a large amount of low-frequency variance in the standardized ring-width series which will hopefully include important long-term climatic information.

A histogram of the autocorrelations for the ring-width indicies is shown in Figure 2b. The standardization process has shown that a large amount of the low-frequency variance detected in the ring-width series was due to the growth trend since removal of this trend shows much reduced autocorrelations through higher lags. However, the histogram does indicate that there is significant low-frequency variance left in the series.

II. Climatic Data

The climatic data were secured from The Pennsylvania State University weather station in State College, Pennsylvania. The climatic data includes



(a) (b)

Figure 2. Old Henry ring-width index series (a) and autocorrelation function (b).

average monthly temperatures in degrees Fahrenheit and total monthly precipitation in inches for the years 1887 through 1981.

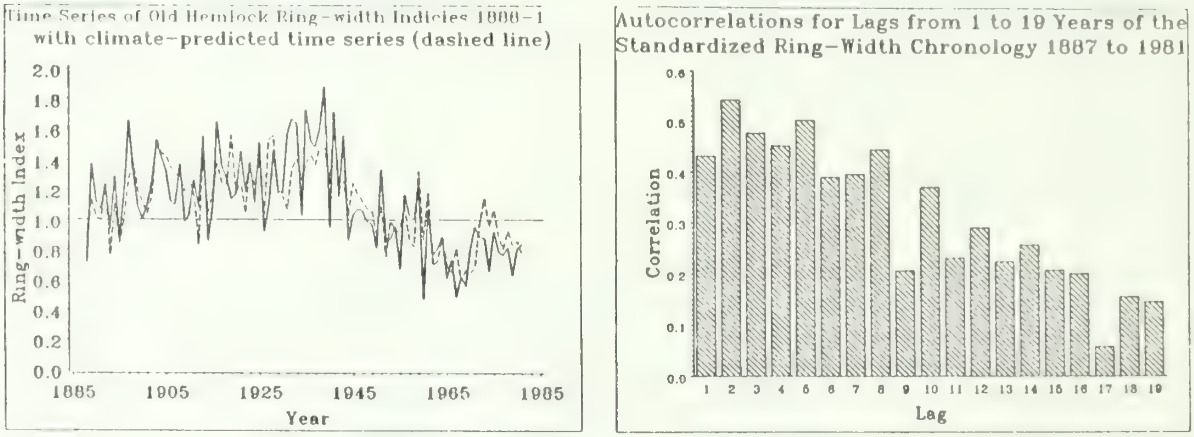
It is interesting to note that the weather station is in close proximity (approximately 8.2 air miles) to the site where Old Henry was growing and that the two sites are at about the same elevation. Thus, the average overall climate for the two areas would be expected to be similar. However, by noting the location of State College in a broad valley, verses that of Alan Seeger in an upper mountain valley, one would expect significant differences in the microclimate between the two areas. Were local climatic variables such as number of frost-free days, average monthly hours of solar radiation and diurnal temperature differences measured, to name a few, the two sites would undoubtedly be found quite different.

Inasmuch as the records of climatic data cover only one-fourth of the record of the Old Henry tree-ring series, the climatic data are the limiting variables in the subsequent modeling process. However, if in the future more ring-width series samples from this region are collected and crossdated with the Old Henry series and other weather station data are secured, the extended length of the Old Henry series would provide an extremely valuable record for modeling past climate for this region (Fritts, 1976).

THE GROWTH MODELING PROCESS

The growth of an individual tree is a compounding process in which not only contemporaneous climatic and environmental variables interact to affect the current year's growth but past climate and radial growth also play a role (Fritts, 1976 and Figure 1b). As such, modeling of current growth must consider those past (lagged) variables in some way. Many different schemes for inclusion of these lagged variables in the modeling process have been proposed and utilized in dendroclimatic modeling (Fritts, 1976; Fritts and Xiangding, 1986; Cook et. al., 1987). This study follows the conventions set forth by Fritts (1976) and includes as independent variables monthly

temperature and precipitation lagged one year such that 14 months of data (June of the previous year through July of the current year), in the form of 28 independent variables, is associated with the current year's standardized ring-width index value. In addition, to account for the effects of autocorrelation in the series, three previous years (lags 1, 2 and 3) of the ring-width index chronology are also included as independent variables. Thus a total of 31 independent variables are potentially available to model the 94 year ring-width index series from 1888 through 1981 (note that one year is lost because of the use of lagged climatic data). Summary statistics for this reduced ring-width index series are presented in Table 1c. The autocorrelation function for this series is presented in Figure 3b. Note the moderately high autocorrelations at lags of 1, 2, 3, 4, 5 and 8 years.



(a) (b)

Figure 3. 94-year ring-width index series (a) and autocorrelation function (b).

Response surface methodology was attempted for this series (Fritts, 1976). Inspection of the correlation matrix indicated that the independent variables were very nearly pairwise orthogonal to begin with, implying that little would be gained from a principal components (PC) rotation. Indeed a principal components analysis (PCA) of the climatic variables shows that the first PC accounts for only 10 percent of the variability, the first 12 PC's for only 68 percent and the first 20 for 90 percent. Thus the method was abandoned as it appeared that nothing would be gained from PCA (Johnson and Wichern, 1985) and a step-wise regression model on the original variables was pursued instead.

Correlation analysis indicated that all three lagged ring-width index variables might be positively correlated with the current year's ring-width index value and that the previous year's June temperature might be negatively correlated. No other obvious relationships could be inferred from the correlation matrix. PROC STEPWISE was used in SAS to perform the step-wise regression (SAS, 1985). The resulting model had an $R^2 = 0.64$ and Mallow's Cp = -3.78. The fitted model follows.

$$\hat{Y}_t = 1.829 - 0.045T_1 + 0.125T_2 + 0.008T_8 + 0.009T_{10} +$$

$$0.026P_{10} + 0.034P_{13} + 0.035P_{14} + 0.502R_2 + 0.229R_3$$

where: $\hat{Y}_t$ = predicted ring-width index — P_{10} = current March preciptation

T_1 = previous June temperature — P_{13} = current June precipitation

T2 = previous July temperature — P_{14} = current July precipitation

T_8 = current January temperature — R_2 = ring-width index lag 2

T_{10} = current March temperature — R_3 = ring-width index lag 3.

The ring-width index series from 1888 to 1981 is plotted in Figure 3a as the solid lines. The predicted series ($\hat{Y}_t$) is plotted as the dashed lines. The predicted series seems to fit the original data series quite well. Note that the effect of the lagged growth variables included in the model are apparent in some instances as witnessed by a "shifting" of the expected response to the right (e.g. 1965 to 1970). From this observation and Figure 3b it is evident that the model may benefit from the inclusion of the lower-order lags mentioned above. It is also evident that the climatic variables selected for inclusion into the model tell only part of the story. Inclusion of more site-specific climatic variables (were they available), trying different standardization functions and time series techniques such as ARMA modeling (Fritts, 1986) are all viable alternatives in the modeling process.

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THE RELATIONSHIP BETWEEN TREE DIAMETER GROWTH AND CLIMATE IN THE LAKE STATES

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ABSTRACT. This study identified climatic variables that significantly influence diameter growth of trees in the Lake States. 1) A regional tree growth model was used to account for the variability in diameter growth due to stand and tree effects; and 2) a correlative approach was used to analyze the remaining unexplained average diameter prediction errors by species for monthly and seasonal precipitation and temperature variables. Remeasurement data collected during the recent Michigan and Wisconsin forest inventories, plus data from four National Forests and one experimental forest were analyzed. The influence of moisture regime was minimized by using only plots from frequently occurring moisture classes. Only dominant, codominant, and intermediate trees were used. The climatic influences most beneficial to diameter growth in conifers were high levels of intense precipitation ($\geq .5$ inch) in the fall, cold falls and winters, and greater July precipitation. For the hardwoods, greater June precipitation, low proportion of rainfall in the fall, and high levels of intense summer precipitation were the most beneficial. Climatically sensitive conifers in the Lake States in order of decreasing sensitivity are: white spruce, jack pine, hemlock, red pine, balsam fir, and white pine. For hardwoods, they are: quaking aspen, paper birch, bigtooth aspen, black ash, white ash, and sugar maple.

INTRODUCTION

Climate has long been recognized as an important environmental factor affecting tree growth. Precipitation is generally considered to be the most important of the climatic factors. However, in northern areas where precipitation is normally adequate, temperature may become the most influential. Seasonal or monthly precipitation or temperature patterns are often more important in explaining variations in tree diameter growth than annual values. Different studies (Coile 1936, Tryon et al. 1957) have shown different climatic measures to be significant depending on the species, the variables examined, their range of values, the manner in which they are expressed, and the region over which they are studied.

Analysis of tree growth for relationships with climatic factors is difficult due to the large variability in tree growth patterns due to stand, tree, and site effects. The unexplained variability can be reduced by using a regional tree growth model, such as Lake States STEMS (Belcher et al. 1982). Changes in tree growth and mortality caused by factors such as species, tree size, competition, crown ratio, and site quality, can be largely accounted for by such a model.

The objective of this study was to identify precipitation and temperature

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variables that significantly influence diameter growth of trees in the Lake States. This was accomplished by 1) using a regional tree growth model, Lake States STEMS, to account for the variability in tree diameter growth due to the effects of stand, tree, and site factors; and 2) then analyzing the remaining errors in diameter growth predictions by species for monthly and seasonal precipitation and temperature variables. A first step towards developing a climatic model for the Lake States.

STUDY AREA

The study was confined to forest lands systematically sampled across all of Wisconsin, all of Michigan except for three National forests, and the Chippewa National Forest and the Cloquet Experimental Forest in northern Minnesota.

Minnesota

The Chippewa National Forest is located in north central Minnesota. Retreating glaciers left a landscape of flat to gently rolling terrain which is interrupted by areas of low hills and numerous wetlands. The vegetation of the forest reflects its position near the boundaries of three major vegetative communities--the coniferous forest to the north; the hardwood forest to the south; and the prairie to the west. The University of Minnesota's Cloquet Experimental Forest in northeastern Minnesota lies on a glacial outwash plain containing scattered low ridges, knolls, and bogs. Upland vegetation types occur on two-thirds of the forest; lowland types on the remainder. The climate of the two Minnesota study areas is typically continental, with warm summers and cold winters. Mean annual temperatures are about 39 degrees F. Annual precipitation at Cloquet is 30 inches; across the Chippewa National Forest it varies from 23 to 27 inches.

Wisconsin

Glaciation has profoundly affected Wisconsin's physiography except for the southwestern corner. A plateau extends across northern Wisconsin. The climate of Wisconsin is typically continental. Lakes Michigan and Superior modify adjacent areas by reducing summer temperatures and increasing winter temperatures. Average annual temperature varies from 39 to 48 degrees F and total annual precipitation from 29 to 34 inches.

Michigan

Michigan is composed of two large peninsulas jutting into the world's largest bodies of fresh water, giving most of the State a quasi-marine climate. The Great Lakes and variation in elevation play an important role in determining Michigan's climate. Roughly half of the State is covered by level terrain or gently rolling hills. However, the western half of the Upper Peninsula and the northern half of the Lower Peninsula contain elevated tablelands. Michigan's average annual temperature varies from 41 to 50 degrees F and the precipitation averages between 27 to 37 inches.

GROWTH DATA

The growth data came from available remeasured forest inventory plots from seven areas in the Lake States (Table 1). The Cloquet plots were all 1/7-acre fixed-radius plots with tree diameters greater than 4.9

inches recorded. The State survey and National Forest plots, systematically sampled across each area, were variable-radius plots consisting of 10 points uniformly spaced over an acre. At each point, trees 5.0 inches dbh and larger were sampled with a 37.5 factor prism. At the first three points tree saplings (dbh 1.0 to 4.9 inches) were recorded for 1/300-acre subplots.

Table 1. Distribution of remeasurement plots used in the data analysis along with number of plots (disturbed plots removed) and measurement years.

Area	Number of plots	Dates of Measurement Initial	Final
Minnesota			
Chippewa National Forest	77	1969	1979
Cloquet Experimental Forest	199	1977	1983
Wisconsin 1/			
State Survey	1,291	1967-69	1981-83
Chequamegon National Forest	100	1975	1981-83
Nicolet National Forest	126	1974	1982
Michigan 1/			
State Survey	520	1964-66	1978-81
Huron National Forest	95	1977	1982-83
	2,408		

1/ State Survey conducted by Forest Inventory and Analysis Unit, North Central Forest Experiment Station, St. Paul, Mn., on non-National forest lands only.

The following data were recorded for each plot: plot site index, tree dbh, species, status (live, cut, dead), and live crown ratio. All Survey and National Forest plots also included moisture class, crown class, and plot history. Field methods and coding criteria for these plots are described in Doman et al. (1981). Major effects from human and natural causes were excluded by eliminating plots with a history of disturbance, which showed at least a 10 percent decrease in stand basal area.

To prevent confounding topographic relationships with macroclimatic factors, the data base was screened to select only plots on frequently occurring moisture classes for each covertype. For the pines, only plots in moderately dry and well drained sites were used; for black spruce, tamarack and northern white cedar plots occurring on moderately wet and very moist sites were retained; all other species were confined to well-drained and moderately moist sites with the exception that the oak-hickory type could appear on moderately dry sites.

To minimize the influence of crown position on growth patterns, only dominant, codominant, and intermediate trees were included in the data-base. Open grown and suppressed trees were not used. Scattergraphs of the average projection errors by species on dbh classes by crown class indicated that open grown and suppressed trees behave in a distinctly different manner than dominant and codominant trees. Intermediate trees were in a transition class between the two groups and were retained to increase sample sizes. Results suggest that the macroclimate has a more direct influence on overstory trees than on understory trees, which are more likely responding to the microclimate or whose growth is dominated by competitive effects. Dominant, codominant, and intermediate trees found on plots of frequently occurring moisture classes totaled 31,700 trees.

The STEMS growth projection model (Holdaway and Brand 1986) was used to remove the component of growth attributed to stand dynamics. The differences between predicted and observed diameter growth are due to growth model errors, a part of which may be attributed to climatic variation not explicitly accounted for in the STEMS model. Other unaccounted sources of variation included soil type, moisture class, topography, other more localized climatic variations, and anthropogenic disturbance.

CLIMATIC DATA

The climatic data were obtained from yearly "Summary of Month" data tapes from the National Oceanic and Atmospheric Administration Network of Climatic Data Acquisition Stations (NOAA 1986). The most complete long term records were available for nine climatic elements. Therefore, the selection of variables to be used was restricted to certain expressions of these nine elements. The failure to consider such factors as heating and cooling days, evaporation measures, and freeze data is the result of the incompleteness of such records rather than failure to recognize their possible importance. Even for these nine elements, the data tapes contained frequent missing values. Stations with more than 7.5 percent of these observations missing were deleted--leaving 270 stations. Missing values for these stations were estimated using 24- or 30-year average values from the closest station from among 99 main stations (NOAA 1982).

Climatological data could not be obtained directly for each plot and so they were estimated by the climatic conditions of the nearest weather station. The most frequently occurring measurement and remeasurement year were calculated for all plots assigned to each station. Plots in the same locality were usually measured in the same year. The climatic data for each station in the study were averaged over the measurement interval of the plots assigned to the station.

The following climatic measurements were selected as the basis for the present study: average minimum, mean, and maximum temperature; total and proportional precipitation; snowfall; temperature range (ave. max. July temp. - ave. min. Jan. temp.); number of days precipitation $\geqslant$ .1 inch; number of days precipitation $\geqslant$ .5 inch; number of days minimum temperature $\leqslant$ 0 degrees F; and number of days maximum temperature $\geqslant$ 90 degrees F. The more common variables were summarized by month and seasonal values; all the rest were reduced to seasonal values (Table 2). Meteorological winter includes December through February; spring, March through May; summer, June through August; and fall, September through November.

Table 2. List of the monthly and seasonal values of the climatic variables used.

Variable description	Monthly	Seasonal	Annual	Number of variables
Temperature				
Mean temperature	X	X	X	17
Mean maximum temperature		X		5
Mean minimum temperature		X		5
Range			X	1
Number days $\leqslant$ 0 degree		X	X	5
Number days $\geqslant$ 90 degree		X	X	5
Precipitation				
Total	X	X	X	17
Proportional (Total/Annual)	X	X		16
Snowfall	X		X	13
Number days $\geqslant$ .1 inch		X	X	5
Number days $\geqslant$ .5 inch		X	X	5

STATISTICAL ANALYSIS

The factors affecting growth are so numerous that it is often difficult to isolate the ones having the greatest influence. Practical limitations necessitate rejection of a great many of the more complex climatic indices. A large number of them are simply manipulations of the basic climatic data and thus highly correlated with the original variables. Or, as with the length of growing season, are closely related to the temperature or precipitation regimes. Such manipulations can have little influence upon the fact of whether or not a true correlation exists.

The large number of potential independent variables also precludes any straightforward interpretation of regression results. Preliminary data analyses were undertaken to reduce the number of independent variables and to limit multicollinearity between the variables. The final predictor variables were chosen to satisfy the following conditions: 1) well correlated with diameter growth predictions, 2) have relatively low correlations with other climatic variables, and 3) show similar trends over a number of species to eliminate random phenomenon.

Each species with more than 300 tree growth observations was analyzed separately. The dependent variable was the average annual diameter growth prediction error by climatic station and species over the measurement interval. The independent variables were the 94 initial climatic variables averaged over the measurement interval. The first step was simple correlation analysis between the growth errors and the climatic variables for all species. The next step was to select from groups of interrelated variables the single variable within the group that was the most strongly correlated with tree growth. Each season and the months within it were considered a group for the common temperature and precipitation variables. For example, only the variable with the highest correlation to diameter growth errors could emerge from among these precipitation variables: total or proportional summer precipitation or total or proportional monthly (June, July, August) precipitation.

For the four "number of days" variables (Table 2), the single strongest seasonal or annual variable was used. Snowfall showed monthly correlation trends but no seasonal trends and so was represented by the single strongest monthly variable. When two variables in a group were highly correlated with the growth errors, as well as with each other, the one less correlated with the remaining independent variable pool was used. These strong trends had to appear across a number of species. Because of high correlations (>.90) between spring and summer temperatures and fall and winter temperatures (for maximum, mean, and minimum values), two new variables were created using average cold season temperatures (fall + winter) and average warm season temperatures (spring + summer).

Preliminary determinations were made of the climatic variables to retain. Using these variables, multiple linear regression analyses were run for each species. Only species in which the climatic influence was strong enough to account for at least 25 percent of the variability in residuals were retained in the analysis. The variables retained in the final stage were then re-evaluated, analyzing the conifers and hardwoods separately.

RESULTS AND DISCUSSION

The goal of this study was to determine which predictor variables are important in describing the pattern of the diameter growth errors. For this, the correlation coefficients of the initial variable pool are of interest because they indicate the relative importance of the corresponding climatic variables both by their magnitude and sign. Since the ultimate aim in further studies will be the formation of a climatic model that uses a basic set of climatic variables, multivariate techniques, such as principle components analysis, were not explored at this time.

Based on the criteria previously set forth these final predictor variables were chosen for the conifers and hardwoods (Table 3). The main climatic variables related to growth of conifers and hardwoods are listed by decreasing relative importance. Ranking was achieved by averaging all correlation coefficients (significant at P=.001) for climate sensitive species with the requirement that all correlation coefficients included must show the same directional effect. Number of days per season with maximum temperature ≥ 90 degrees F was dropped--no trends were evident across species.

Table 3. Average correlation coefficients for all climatically sensitive conifers and hardwoods with STEMS tree growth errors (P=.001) listed in descending order of importance. The sign of the correlation coefficient indicates whether the variable has a positive or negative effect on tree growth. Only species with similar effects are used in the calculations.

a) CONIFERS 1/

Independent variable	Average correlation coefficient	Number of species in average
PREC ≥ .5 INCH FALL 3	+.420	4
TEMP ≤ 0° F FALL 3	+.392	5
MAX TEMP COLD SEASON	-.390	5
PROP PREP DEC	-.372	4
PREP JULY	+.360	6
PROP PREC FALL	+.340	3
RANGE	+.328	5
PREC MARCH	+.325	4
PREC ≥ .1 INCH SUMMER 3	+.306	5
MIN TEMP WARM SEASON	-.270	4
SNOWFALL NOV	+.240	3

b) HARDWOODS 2/

Independent variable	Average correlation coefficient	Number of species in average
PREC JUNE	+.400	4
PROP PREC FALL	-.356	5
PREC ≥ .5 INCH SUMMER 3	+.352	4
MIN TEMP COLD SEASON 3	-.318	4
TEMP ≤ 0° F FALL	+.317	3
RANGE	+.300	4
PROP PREC SPRING	+.295	2
MAX TEMP WARM SEASON	+.270	2
PREC ≥ .1 INCH SUMMER 3	+.268	4
PROP PREC DEC	-.265	4
SNOWFALL MAR OR SEPT	-.180	4

1/ Jack pine, red pine, white pine, whit spruce, balsam fir, and hemlock
2/ Black ash, sugar maple, bigtooth aspen, quaking aspen, and paper birch
3/ Number of days of ...

The strongest climatic influences beneficial to diameter growth of conifers include:

1) high levels of "effective" precipitation (≥.5 inch) in the fall,
2) cold falls and winters,
3) low proportion of the total precipitation in December, and
4) higher amounts of precipitation in July.

The strongest climatic influences beneficial to diameter growth of hardwoods are:

1) high June precipitation,
2) low proportion of rainfall in the fall, and
3) high levels of effective summer precipitation (≥.5 inch).

Certain interesting differences appear between the conifer and hardwood species:

1) fall precipitation is strongly beneficial to conifers but is less beneficial to hardwoods, while summer precipitation appears more important to hardwoods,
2) increased July precipitation was related to increased conifer growth; increased June precipitation increased growth of hardwoods,
3) in the cold season conifers benefit from lower high temperatures and hardwoods from lower low temperatures,
4) in the warm season growth of conifers is enhanced, but to a lesser extent, by lower low temperatures, whereas hardwoods benefit more from higher high temperatures, and
5) the magnitude of the average correlations indicate that conifers are more sensitive to climatic influences in the Lake States than the hardwoods.

Some general observations can be made from the data analysis. Although all three temperature measures (minimum, mean, and maximum) were well correlated with diameter growth in each case tested, either the maximum or minimum value provided slightly more information than the mean value. Growing season temperature has less influence on tree growth than the cold season temperature, which influences the growing season indirectly by limiting its length. Effective precipitation (≥.5 inch) has a stronger relationship to growth than moderate intensity precipitation (≥.1 inch). Regarding snowfall, conifers grew better when early snow came in November; hardwoods grew slower when there was either late snowfall in March or very early winter snowfall in September. However, in general, snowfall had a minimal effect on all species in the Lake States. Finally, annual values provide far less information than monthly or seasonal values for all basic temperature and precipitation variables.

A final multiple regression was run on all species using the variables listed in Table 3 except that snowfall was eliminated due to its relatively low correlation with growth and because of its high correlation with average minimum cold season temperature (-.88). Coefficients of determination (R^2) from multiple regression analysis were used to categorize the relative sensitivity to climate of the various species, as follows.

Climatic sensitivity (R^2 as a percent)		
Strong	**Moderate**	**Weak**
Jack pine (55)	Red pine (35)	Black spruce (5)
White spruce (66)	White pine (24)	Tamarack (10)
	Balsam fir (33)	N. white cedar (13)
	Hemlock (39)	Red maple (11)
	Black ash (29)	Elm (5)
	Sugar maple (26)	Yellow birch (18)
	White ash (26)	Basswood (7)
	N. pin oak (25)	White oak (3)
	Bigtooth aspen (29)	N. red oak (1)
	Quaking aspen (34)	
	Paper birch (33)	

CONCLUSIONS

This study has shown that after adjusting for differences in species, size, site, and competition, significant portions of unexplained variation in the growth patterns can be accounted for by macroclimatic variables. The nature and magnitude of the relationships varied by species. Macroclimatic variability appears to have significant potential to increase precision of diameter growth estimates for regional growth models.

The results demonstrated that tree species in the Lake States showed the greatest response to fall and winter climate, especially for the conifers. Certain aspects of summer precipitation were important, especially for the hardwoods. Spring temperature and precipitation are not as important to tree diameter growth in this region as they are in regions of more limited precipitation (Tryon et al. 1957).

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THE ROLES OF MODELS IN THE FOREST RESPONSE PROGRAM

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ABSTRACT. The Forest Response Program is a US Environmental Protection Agency and US Forest Service interagency research program on the effects of acidic deposition ("acid rain") on trees and forests. The program plans to use a diversity of models to accomplish several goals. Two primary goals are to understand the effects of sulfur and nitrogen deposition on trees and forests and to be able to predict the response of trees and forests to alternative deposition scenarios.

Achieving these goals will require many modeling efforts along the way. Modeling is used extensively in planning. Early model analysis helps to determine further needed empirical work. In addition, qualitative analysis of the models themselves (through loop analysis) will help to determine which models or aspects of models require further detailed attention. This approach focuses the modeling effort and avoids unnecessary modeling which is not needed for the Program.

A major aspect of the modeling effort within the Program is to understand the ways in which the many models and their roles fit together. Here, several ways of classifying models are presented. A scheme using biological levels of organization is presented as the backbone of the modeling effort. In particular, whole tree physiology-based models of individuals trees will be integrated into individual-tree stand models. The emphasis is on a modeling system and we resolve the generality, realty, and precision dilemma in favor of generality and reality.

INTRODUCTION

THE PURPOSE OF THIS PAPER

Both "roles" and "models" are intentionally plural in the title of this paper. The Forest Response Program (FRP) must use a variety of models and modeling efforts to achieve its goals. The purpose of this paper is to give an account of the diversity of models that will be used in the FRP and then to show how this diversity will be structured or organized to make it useful. It is one thing to say that a program will use a variety of models and another to ensure that a "sack of doorknobs" does not result.

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BACKGROUND ON THE FOREST RESPONSE PROGRAM

The Forest Response Program is an interagency program of the US Environmental Protection Agency and the US Forest Service. It operates as part of the National Acid Precipitation Assessment Program (NAPAP). The goal of the FRP is to answer three policy questions (see Table 1) about the effects of acid precipitation and associated pollutants on trees and forests. The FRP intends to answer these questions by producing five Major Program Outputs between now and 1991 (see Table 2).

Policy Question 1: Is there a significant problem of forest damage in North America which might be caused by acidic deposition, alone or in combination with other pollutants?
Policy Question 2: If so, what is the causal relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?
Policy Question 3: If there is a causal relationship, what is the dose-response relationship between acidic deposition, alone or in combination with other pollutants, and forest damage in North America?

Table 1. Forest Response Program Policy Questions

1. Evaluation of the extent and magnitude of recent changes in forest condition (12/88).
2. Evaluation of the role of non-air pollution factors in growth reduction and visible decline (12/88).
3. Quantitative estimates of seedling responses to S, N, and associated pollutants at ambient conditions (2/88 and annually).
4. Evaluation of the roles of S, N, and associated pollutants in forest decline (4/89, 4/91).
5. Projection of responses under alternative deposition scenarios (12/91).

Table 2. The Major Program Outputs and their expected completion dates.

THE STRUCTURE OF THIS PAPER

I will describe four ways that models can be classified in an attempt to describe both the diversity of models and modeling approaches that the FRP will use and to highlight several of the trade-offs that must be considered in choosing between various modeling methods and styles. This will be followed by an overall conceptual framework which attempts to organize the modeling and data analysis efforts into a conceptually coherent whole. I will then discuss an example area of modeling that raises specific issues about which the program is concerned.

CLASSIFICATIONS OF MODELS

Models are tools and may be classified in a great variety of ways. Just as the tools of the carpenter and the tools of the printer are organized differently, so can the many types of models used by biologists working with trees and forests.

CENTRALITY OF MANAGEMENT

In a large program, models may be classified by the degree of control that the central management of the program might want to exercise. Some programs have considered all models the same in this respect, either exerting no control over the models or attempting to produce only a single centrally managed model. The FRP recognizes that management interacts with the modeling effort in diverse ways. A classification on this basis is the following.

1. Research Tool Models. These are models developed by Principal Investigators (PIs) as their research progresses for any reason whatever and in any style. Their job is to help the PI. Such models attract little or no interest from central management, except as sources of information.

2. Local Expert Models. These are larger, usually complex models that represent the accumulation of a great deal of information and work on the part of the forestry community which apply to a given species or region. The well-known growth and yield models such as STEMS, PTAEDA, and PROGNOSIS (to mention only a few) are examples of this type of model. These models can be used as important components of a research program to identify pollution effects. For example, data on growth and natural environmental variables can be fitted to these models and the residuals examined for possible associations with pollution. In the case of local expert models, central management may be more interested in the models because of their importance in the overall program. Although these models are used more or less "off-the-shelf," central management is further concerned that two aspects are developed as appropriate to the given model. The first is that the assumed mechanism of action of pollution in the models be specified explicitly if possible. (It may not be possible; pollution may reside in the error term). The second concern is that estimates of confidence intervals on the projects of the model be given. In the context of the FRP, confidence intervals are at least as important as the projections themselves. This is not a trivial requirement in most cases. Many local expert models have taken a great deal of time and effort just to get to the point of making projections. Adding confidence interval estimates is almost as large a task. Nonetheless, they are critical for a model that is to be used in this Program.

3. Synthesis Models. These are models constructed with close guidance from central management to synthesize the information gathered across the entire Program into the Major Program Outputs. However, even though these models are centrally managed, it is important to realize that the goal here is a modeling system, not a single model. This spirit of modeling dovetails

with modern software engineering concepts (see Brooks, 1979, for the management issues). Implementation is done via the construction of libraries of small modules of computer code which are designed to be useful in a large variety of situations. The computer language chosen to implement such modeling systems must encourage such an approach.

Synthesis models may therefore start life as box-and-arrow diagrams. Each box can then become a module in a simulation model. At first, the contents of the box can be a constant, later a function or complex simulation in itself. The overall model assembled from the parts should not depend upon the detail actually in the boxes.

The modular approach also makes it possible for work to be done on the modeling system at many locations by many different groups. Although centrally managed, the actual coding effort can be distributed if attention is paid to careful programming management.

The modular approach also makes it easier to provide Quality Assurance and Quality Control (QA/QC) for the actual code that makes up the models. Because each module is tested separately and stored in the library with a test driver, QA/QC can be made a routine part of the effort. A Source Code Control System (see, for example, Kernighan and Pike, 1984) coupled with a library manager can automate this process.

GENERALITY, REALITY, AND PRECISION

Levins (1966; see also Puccia and Levins, 1985) has introduced a useful classification of models in population biology which also applies to the models to be used by the FRP. Levins claims that modelers try to simultaneously maximize three desired properties of a given model: generality, reality, and precision. He then argues that any one model sacrifices one of these desired properties to achieve more of the other two. The argument is based on an analysis of a number of models used in population biology. Models are therefore classified by which property is sacrificed for the other two.

In traditional growth and yield models it is fair to say that generality is sacrificed for increased reality and especially precision. If the goal of the model is to predict yield on a specific plot at a specific time this is, of course, the best strategy to take.

For the purposes of the FRP synthesis models, however, a different trade-off is needed: The FRP must emphasize generality and reality at the expense of precision. The Policy Questions which drive the Program require answers at a level of generality that is greater than is required by a specific growth and yield question. The importance placed by the Program on an understanding of the physiological mechanism of action of a pollutant dictates that reality must be maximized in the models as well. Therefore, precision will have to be sacrificed. It is

important to realize that these trade-offs are not black-and-white for the synthesis models, and that for the research tool and local expert models other choices may be made.

BIOLOGICAL LEVELS OF ORGANIZATION

Work within the FRP occurs at many levels of biological organization. Models as well may be classified by the level of organization to which they apply. The FRP distinguishes four levels of organization in its modeling efforts: seedling physiology (growth); whole (mature) tree physiology (growth and mortality); stand growth and yield; and regional growth and yield. Models may either apply to a single level of organization or may serve to link two levels of organization. For example, much of the experimental work in the Program is conducted on seedlings for obvious practical reasons. But it is important that the connection between seedling physiology and mature tree physiology be made. Although this is an outstandingly difficult problem, models may help.

The four levels of organization chosen represent the results of decisions to focus the scope of the Program. Both subcellular processes in the sense of specific biochemical pathways and community level processes such as the maintenance of diversity are left out. These may be addressed by Research Tool Models or may be brought into the Synthesis Models if necessary. The biological levels of organization approach also does not include effects on trees and forests which are not biological such as recreational use and esthetics. These are not included because the Program must focus on biological research.

RADIUS OF INFORMATION

An important dichotomy in modeling has to do with the work a model is being asked to do. Models may be used to either make quantitative projections or to summarize our current understanding of how the world works. While this dichotomy has value in helping to understand the diversity of models, it is also true that most models are a mixture. The nature of this mixture is important when a modeler is faced with "extrapolating beyond the data." If one is restricted to empirical (or, as they are commonly called, statistical) models, then extrapolating beyond the data is difficult or impossible. Physiological process models are not as good at quantitative projection but may expand the range over which projections may be made. Figure 1 illustrates this for an arbitrary parameter p (which could be a measure of acidic deposition) and a response function f (which could be the growth response of a stand). The modeler will have direct data on p and f for a limited range of values of p. Over this range an empirical model is possible. However, extension of the modeling effort to include a process-based model as well may extend the range over which f may be understood. Figure 1 shows the unfortunate case where the region of interest is still greater than we can cover in the mixed modeling effort (this could be the case if future more extreme values of deposition needed to be

considered). Figure 2 shows the fortunate case where the mixture will allow examination of the entire range of interest. In general the region of interest is not known at the outset of a research program so methods for expanding the range must be at hand.

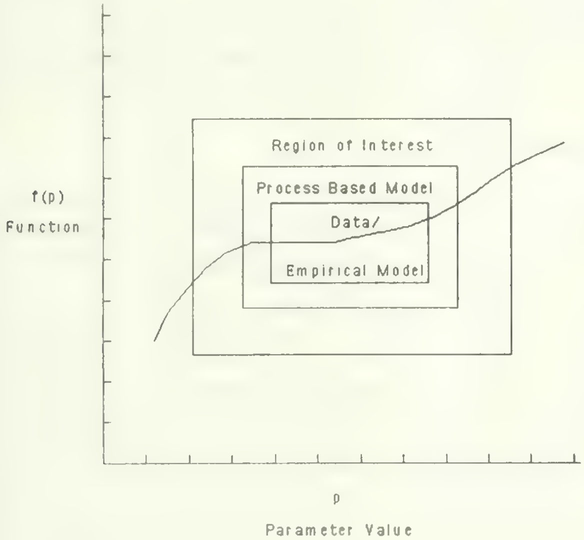

Figure 1.

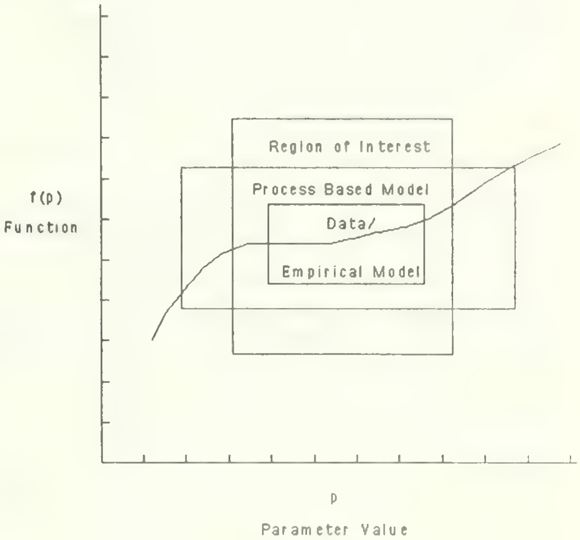

Figure 2.

STRUCTURING THE DIVERSITY OF MODELS

PLANNING FOR MODELING

In a program such as the FRP planning for the modeling effort is an integral component of the overall planning activity. Modeling tasks must be identified and resources allocated to them. The uses of particular models must be specified. It is important to plan for flexibility since requirements may change as our understanding of the science improves or as the questions of the policy makers change.

MODELING FOR PLANNING

Relatively simple models are important at early stages of the Program to aid in planning research. Models are needed to identify missing data and also to give ideas on the type and amount of data that may be needed to answer a question. Models do not constitute the only method of planning, however. Information of many kinds must feed into the planning process.

QUALITATIVE AND SENSITIVITY ANALYSES

Early versions of models of the box-and-arrow type may be subjected to qualitative analysis. Even if the internal structure of the boxes is poorly specified, important information may be gained by analyzing the interactions of the components themselves (Levins, 1974). One technique is loop analysis (Levins, 1974;

Puccia and Levins, 1985). Here the relative importance of each box or arrow in the model can be determined. This method is potentially valuable as a planning exercise in that it can suggest which boxes should have their details filled in first. This could help to focus the modeling effort and avoid modeling that is not necessary. Loop analysis is only one method of sensitivity analysis. Other, more sophisticated, methods can be developed for more complex models (see Makela, this volume)

VALIDATION AND INTER-MODEL COMPARISON

Along with the diversity of models considered by the FRP are a corresponding diversity of methods of validation. Naturally, empirical models will have to be validated by data sets similar to those from which the models were created. However, process-based and mixed models may be validated in other ways such as by reference to particular experimental results. That is, the models may be validated by validating their assumptions. Other models will not be validated directly, but will need to be subjected to Monte Carlo methods to determine the range of possibly valid results. Another technique may be to compare model outputs. A stand model which contains components of a process-based physiology model may be partially validated by comparing its output, say the diameter distribution, to the patterns generated by an empirical model.

Comparison of models is also an important research task. For example, the Local Expert Models all predict changes in stand productivity based on changes in individual tree growth. These various predictions of the different models which apply to different species in different regions need to be compared. The Program needs a methodology for making such comparisons in a quantitative fashion.

STAND DYNAMICS AS THE PIVOT

Although the FRP is concerned with several levels of biological organization, there is a sense in which the level of stand dynamics is the most important. The internal processes of tree physiology and the external processes of the environment meet at the level of the stand. Trees in stands do not behave like individual trees. In particular trees under stress (as from pollution) in stands do not behave the same as isolated trees under stress. Hyink and Zedaker (1987) have emphasized the role of stand dynamics in simply detecting decline of forests and their arguments applied with even more force to unraveling pollution caused forest decline. Normal stand dynamics is the background against which any pollution effect is set.

Hyink and Zedaker (1987) argue that the complex interplay between the genotypes of the trees, the environment, and the genotype-environment interaction must be understood before pollution effects (or any other) can be understood. This genetic view of stand dynamics is valuable, but a demographic view of stand dynamics is needed as well. In the demographic view, the parameters of birth rate, mortality rate, and growth rate depend

on the environment and on the competitive interactions of the trees. Of course these parameters depend on the genetic constitution of the trees, but we frequently do not have that information. Also a single model cannot usually contain genetic richness as well as complex environmental dynamics. However, whether the genetic or demographic view is used, the important point is that trees, stands, and their environments are constantly changing. Pollution effects can only be understood in the context of normal dynamics.

DISCUSSION

Competition may be taken as an example of the complexities of modeling in a program such as the FRP. First, competition is clearly an important component of stand dynamics. However, it is also true that competition takes place at the level of individual tree physiological processes. Individual trees compete for light or nutrients or water uptake and these processes must be modeled at a physiological level. Competition undoubtedly will appear in models that fall in all of the categories of all of the classifications. The job of the Forest Response Program is to make the best use of all of the approaches to modeling competition or any other aspect of trees and forests as they are effected by acid deposition.

This is not an easy task but we have a good chance of succeeding for two reasons. First, the Program is attempting to build on the tremendous amount of relevant work that has preceded it. Second, by adopting a distributed, team, approach to the synthesis models, the Program can utilize the talents of many people.

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Analysis and Modelling of Forest Growth Trends Along a Sulfate Deposition Gradient in the North Central United States

Stephen R. Shifley[1]

Abstract. Levels of emission-related sulfate deposition in the Lake States increase f approximately 1 kg/ha/yr in northwestern Minnesota to 18 kg/ha/yr in southeastern Michigan. Annual tree diameter growth rates for jack pine (*Pinus banksiana*), red p (*Pinus resinosa*), balsam fir (*Abies balsamea*), sugar maple (*Acer saccharum*), and (*Populus tremuloides*) trees were analyzed on 170 forest inventory plots located alo gradient. The Lake States STEMS/TWIGS tree growth projection models were us account for variation attributable to differences in initial tree and stand conditions. Remaining differences between observed and predicted growth rates were analyzed trends related to the estimated sulfate deposition at each site. Preliminary results sh weak but statistically significant negative relations between observed tree diameter patterns and sulfate deposition levels for trees between 13 and 25 cm dbh. Additio analyses are needed to account for differences in climate along the gradient and to c other estimates of sulfate deposition or impact.

INTRODUCTION

Acid deposition has been implicated as a cause of forest decline in Europe and the e United States, and more recently it has been suggested as a possible cause of fores in the southern United States. In each of these cases forest decline or damage was observed and efforts were then initiated to discover the cause. The approach of th is different in that widespread forest damage or decline is not clearly evident durin Lake States (Minnesota, Wisconsin, and Michigan). Rather than attempting to exp observed decline, this research is aimed at detecting subtle regional trends related t deposition; it serves as a pilot study to provide background necessary to support th development of large-scale methods for monitoring effects of pollution on forests. of related studies is in progress to describe relations among sulfate (SO_4) depositi and the chemical content of woody tissues and to describe interactions among sulfa deposition, climate, and growth (Ohmann et al. 1987, Holdaway 1987).

Three factors make the Lake States an opportune region in which to examine large effects of acid deposition on forests. First, the region is overlaid with a very regul well-defined sulfate deposition gradient. Nichols and Verry (1985) estimated that emission-related sulfate deposition increased from approximately 1 kg/ha/yr in northwestern Minnesota to 18 kg/ha/yr in southeastern Michigan. Total wet atmo sulfate deposition ranges from about 5 to about 30 kg/ha/yr across the Lake States increases to a peak in the United States of about 43 kg/ha/yr in West Virginia.

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Cooperating scientists in other aspects of this and related studies include Lewis F. Ohmann, Mar Holdaway, Gary J. Brand, Ronald E. McRoberts, Rolland G. Buchman (USDA Forest Service, No Central Forest Experiment Station); David F. Grigal, and Frank Martin (University of Minnesota Departments of Soil Science and Applied Statistics, respectively). Partial funding provided by th Vegetation Survey Research Program under the National Acid Precipitation Assessment Program

(Harris and Verry 1985). Thus, the Lakes States cover the lower one-half to two-thirds of the wet sulfate deposition gradient in the United States. Second, the forest inventory data collected by the Forest Inventory and Analysis Unit of the North Central Forest Experiment Station are stored in a data base management system that allows ready selection of inventory plots with specified characteristics (Hahn and Hansen 1985). Third, a system of individual-tree-based models, STEMS and TWIGS, is available to predict the expected average growth for trees in even-aged or uneven-aged stands of pure or mixed species (Brand et al. 1987).

The null hypothesis for this study is that periodic tree diameter growth is independent of the level of sulfate deposition. That hypothesis can be refuted by evidence that, other factors being equal, tree growth rates change with changing levels of sulfate deposition. In this study, attention is focused on the jack pine, red pine, balsam fir, sugar maple, and aspen forest types. These types were chosen because they are widely distributed across the Lake States and include both conifers and hardwoods and both shade-tolerant and shade-intolerant species.

METHODS

Field Measurements

Sample locations were drawn from a body of more than 20,000 inventory plots established across the Lake States between 1976 and 1982. Before sample selection, five strata or zones of increasing sulfate deposition were delineated with boundaries corresponding approximately to the 1, 2, 4, and 8 kg/ha/yr emission-related sulfate deposition isolines (Nichols and Verry 1985) (Figure 1). To control the effects of growth variation due to

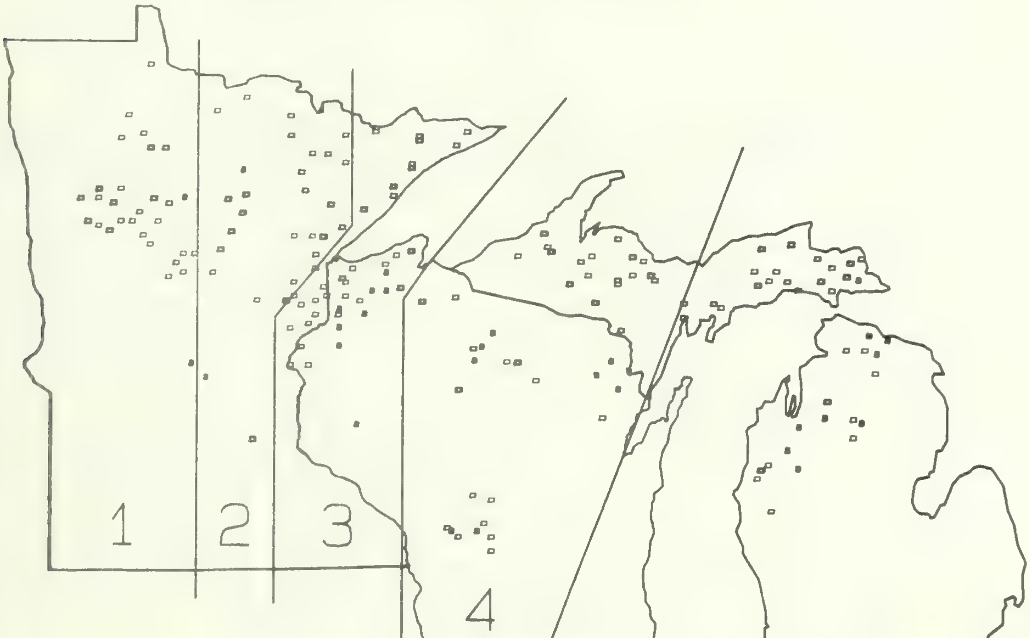

Figure 1. Strata boundaries and locations of the 170 sample plots in Minnesota, Wisconsin, and Michigan.

Table 1.--Initial conditions of plots sampled.

Species	Number of plots	Basal area (m^2/ac) (min-max)	Site index (m at age 50) (min-max)	Stand age (years) (min-max)	Total wet SO_4 (kg/ha/yr) (min-max)
Jack pine	39	15-24	14-20	35-55	6.7-19.2
Red Pine	27	13-30	17-23	17-45	8.7-19.6
Balsam Fir	26	17-31	13-18	45-65	7.3-17.9
Sugar Maple	41	19-35	13-22	45-65	6.7-19.0
Aspen	37	14-25	18-23	35-49	6.1-21.5

natural biological factors on this analysis, sampling was limited to a narrow a range of initial ages, site indices, and densities while still maintaining approximately 8 plots per forest type per deposition zone (Table 1). Plots were randomly selected within each type by deposition zone and age-site-density class.

Field measurements on 170 inventory plots were taken from August through October, 1985, following standard FIA procedures for the Lake States (Doman et al. 1981). The plot design was a 10-point cluster with points systematically located over approximately 1 acre. At each point trees 13 cm dbh and larger were sampled using an 8.6 m^2/ha basal area factor prism. At the first three points trees between 3 and 13 cm were sampled on circular 13.5 m^2 plots. Species, status, dbh, crown ratio, crown class, and merchantable height were recorded for each tree. Presence and cause of damage or disease were also noted. A total of 6,602 trees was measured; additional measurements and samples from trees and soil adjacent to these plots were taken to support related studies based on this set of plots

Estimating Sulfate Deposition

Analysis of growth trends related to sulfate deposition requires an estimate of sulfate deposition at each plot location. Actual sulfate deposition in the Lake States is measured to National Atmospheric Deposition Program (NADP) protocols at approximately 20 locations in the Lake States . Only three stations operated before 1980. This situation makes it difficult to precisely estimate deposition at a particular plot.

Periodic wet sulfate deposition is calculated as the product of the concentration of sulfate per unit volume precipitation and the total volume of precipitation. Mean annual sulfate concentrations as measured by the existing deposition monitoring network could be estimated precisely as a linear function of latitude and longitude and year (between 1979 and 1985)[1]. Precipitation can be quite variable locally and, unlike sulfate concentrations that are measured at only a few locations in the Lake States, precipitation is regularly monitored at nearly 400 locations throughout the region. The 30-year average annual precipitation for each plot was estimated as the distance-weighted average of that observed at the 4 weather stations nearest that plot. Then wet sulfate deposition at each plot was estimated as the product of the estimated precipitation and the modelled sulfate concentration. For this analysis, sulfate concentrations were estimated for 1983 (the midyear for all observed concentrations and the approximate midyear of the observed growth rates), and the precipitation amounts were the 30-year normals from 395 Lake States weather stations. It is possible, using annual precipitation records, to estimate

[1] Based on research conducted with Ronald E. McRoberts and Patrick D. Miles, USDA Forest Service, North Central Forest Experiment Station. Publication in preparation.

deposition for only the remeasurement period. Subsequent analyses will explore that option for estimating site-specific deposition. The 30-year normal estimates used in this analysis are indicative of relative long-term patterns of deposition at the study sites.

RESULTS

The null hypothesis, that periodic tree diameter growth is independent of the level of sulfate deposition at the site where those trees are growing, was tested by comparing observed diameter growth rates with three different estimates of the expected growth rate for each tree. In the absence of effects of sulfate deposition, differences between observed and expected tree growth rates will not show significant trends with the level of sulfate deposition. The following statistical tests do not make an *a priori* assumption that the relation of sulfate deposition to tree growth is strictly a negative one. However, in the first two of the following three tests, the sign of the regression coefficient fitted during the analysis indicates whether sulfate deposition appears to be detrimental or beneficial to tree growth, and discussion highlights those cases where the relationship is both negative and statistically significant.

The model used to test the hypothesis is:

$$\Delta D_i = f(\text{species, tree size, competition, crown size, site quality...}) + g(SO_4) + e_i \qquad [1]$$

where : ΔD_i = periodic annual diameter growth per tree (or basal area area growth per tree)

f(species, tree size,...) = any model predicting growth as a function of biological, edaphic, or climatic factors other than SO_4

$g(SO_4)$ = a function estimating the relationship between wet sulfate deposition (SO_4 in kg/ha/yr) and diameter growth

e_i = the error term, assumed normally distributed with mean zero and constant variance.

The significance of the term $g(SO_4)$ is the subject of this investigation. The first term, f(species, tree size,...), can be any model of forest dynamics capable of predicting tree growth as a function of observable variables (exclusive of the level of SO_4) that describe the current and/or past states of the forest. Climatic factors could also be included in the first term of equation [1]. However, this investigation focuses strictly on the the traditional mensurational descriptors of tree and stand conditions, and climatic variability is not addressed. Results from this analysis will later be expanded to include effects of regional climatic trends.

Analysis started from the simple assumption that the stratification procedures selected trees within each stratum that were growing under conditions so similar that differences in initial site, age, and density were unimportant (i.e. the first term in the right side of equation [1] was zero). To further reduce variation in the initial conditions of the trees used in the analysis, only trees that were initially between 13 and 23 cm dbh were included, and analyses were limited to a single species within each of the five forest types (e.g. only jack pine trees growing on plots in the jack pine forest type were analyzed together), leaving

Table 2.--Results of fitting equation [2] to observed diameter growth rates for trees initially between 13 and 23 cm dbh.

Species	n	b_1	F-ratio	R^2	P-value[a]
Jack pine	306	-.003	14.7	.05	.00
Red pine	338	-.004	4.2	.01	.04
Balsam fir	142	-.003	7.2	.05	.01
Sugar maple	199	.003	4.7	.02	.03
Aspen	206	-.001	1.6	.01	.21

[a] P-value of the F-test for the regression, (i.e. for the significance of b_1).

between 142 and 338 growth observations per species (Table 2). Assuming a simple linear relationship for $g(SO_4)$, model [1] is reduced to :

$$\Delta D_i = \beta_0 + \beta_1 SO_4 + e_i. \qquad [2]$$

The results from regression analyses indicate a significant trend of decreasing diameter growth with increasing SO_4 for jack pine, red pine, and balsam fir. Negative estimates of β_1 indicate reduced diameter growth at higher levels of sulfate deposition. (Table 2). Growth for sugar maples increased significantly at higher levels of sulfate deposition. However, differences in the initial age, site quality, density, and relative tree size are large enough that they could reasonably be expected to have an effect on the observed diameter growth rates. Two other models were explored to account for these factors. The first was the STEMS/TWIGS model calibrated for the Lake States (Brand et al. 1988). The STEMS/TWIGS models are a system of individual-tree, distance-independent models calibrated for these and other Lake States species.

STEMS was used to predict the expected growth of these same trees, taking into account tree size, crown size, size relative to competitors, density, and site quality. Differences between the predicted and observed periodic diameter growth rates for each species were examined for a relationship to the sulfate level. If, for example, SO_4 were having a detrimental effect on tree growth, then the differences between the observed and predicted growth rates should become large and negative as SO_4 deposition increases. The corresponding model is:

$$\Delta D_i = \text{Predict(STEMS)} + g(SO_4) + e_i \qquad [3]$$

where Predict(STEMS) is known and given so that

$$\Delta D_i - \text{Predict(STEMS)} = g(SO_4) + e_i. \qquad [4]$$

By again assuming a simple linear relationship between the left side of equation [4] and SO_4, the relevant model to test the hypothesis is:

$$\Delta D_i - \text{Predict(STEMS)} = \beta_0 + \beta_1 SO_4 + e_i. \qquad [5]$$

The left side of equations [3] and [4] are simply the differences between the observed periodic diameter growth and the STEMS prediction of that growth. The null hypothesis of no sulfate deposition effect is rejected for β_1 significantly different from

Table 3.--Results of fitting equation [5] to observed diameter growth rates for trees initially between 13 and 23 cm dbh.

Species	n	b_1	F-ratio	R^2	P-value[a]
Jack pine	306	-.003	13.3	.04	.00
Red pine	338	-.004	1.2	.00	.27
Balsam fir	142	-.003	7.6	.05	.01
Sugar maple	199	.001	1.5	.01	.23
Aspen	206	-.002	3.4	.02	.07

[a] P-value of the F-test for the regression, (i.e. for the significance of b_1).

zero, and the effects of sulfate deposition are detrimental for negative values of β_1. The results from evaluating model [5] indicate small but significant decreases in diameter growth with increasing SO_4 for jack pine, balsam fir, and aspen (Table 3).

A third model was based only on the information included in the 170 remeasured plots. The observed diameter growth rate was estimated as a linear model of a number of variables observed at the initial measurement. These included diameter, crown class, crown ratio, density, relative tree size, and site characteristics. An F-test (McRoberts 1987) was then used to evaluate the significance of an additional term for SO_4. The models compared in this test were :

$$\Delta D_i = \beta_1 D + \beta_2 C + \beta_3 S + ... + \beta_n B + e_i \quad [6]$$

vs.

$$\Delta D_i = \beta_1 D + \beta_2 C + \beta_3 S + ... + \beta_n B + \beta_{n+1} SO_4 + e_i \quad [7]$$

where: D = tree dbh
C = initial tree crown ratio
S = site index
B = initial basal area per acre.

Other variables are as defined previously, and variables associated with β_4 through β_{n-1} are any variables that help explain the variability in tree diameter growth. In this analysis additional variables included in models [6] and [7] were physiographic class, percent slope, slope position, stand age, crown class, initial trees per acre, mean stand diameter, and tree size relative to the stand average. For red pine and sugar maple, model [7] was a significant improvement over model [6] at the 0.05 level. Results of the F-test comparing model [6], the null hypothesis, with the alternative, model [7], are summarized below:

Species	n	F
Jack pine	306	0.0
Red pine	338	20.5 **
Balsam fir	142	1.8
Sugar maple	199	4.0 *
Aspen	206	0.3

CONCLUSIONS

These preliminary results show trends that make it impossible to exclude wet sulfate deposition levels as a factor in regional patterns of tree diameter growth for these species. At the same time the effects of sulfate deposition are not so great that they overshadow the biological and edaphic factors that have long been held to be the primary factors in tree growth. This is no surprise for if sulfate deposition were a dominant factor controlling tree development in the Lake States, one might well expect to find large-scale forest damage at the southeast end of the gradient.

Definitive conclusions about the impact of sulfate deposition on tree diameter growth in the Lake States will require additional analyses. The role of other potentially important factors, such as climate, has yet to be addressed. Research in the coming months will:

1) Examine trees from a larger range of initial diameters.
2) Try to specifically account for the effects of climate on growth as described by Holdaway (1987).
3) Utilize data on the sulfate content of the soil and woody tissue at each study site as an alternative measure of sulfate impact.

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RISK FACTOR MODELLING FOR FOREST YIELD PREDICTIONS IN ALBERTA, CANADA

T. Singh[1]

ABSTRACT. The boreal forest is a major forest region of Canada, comprising approximately 82% of the forest land in the country. Various risk factors cause errors in prediction and realization of annual allowable cut. A conceptual model was developed to simulate projected expectations, as the probability of losses due to such occurrences are usually predictable for large areas within a given time frame. Preliminary results of such modelling are presented for the McLeod Working Circle in west-central Alberta.

INTRODUCTION

Boreal tree species are of vital importance in the production of sawlogs and pulpwood in Canada; however, forest yields are vulnerable to many risk factors. Forest fires are a common occurrence and often result in destruction of large areas of growing stock. In Alberta, fires have caused an average annual forest area loss of nearly 0.5% over the past two decades. In addition, there are mortality and reduction in growth due to insects and disease infestations.

These problems have not so far been quantified objectively in resource allocation and management, mainly because of a general lack of available tools for such predictions. Many sources of uncertainty affect potential returns and can result in sub-optimal decisions concerning timber supply projections (Marshall 1987). Improved techniques are needed to ensure realistic predictions. Reed and Errico (1986) and Stevens (1986) have developed procedures for optimal harvest scheduling when fire risk is present in western Canada.

The objectives of the risk factor study in the boreal forest of Alberta were: 1) to model the risk of fire to aid management decisions on allowable cut and future timber supplies; 2) to determine the frequency of large-scale insect and disease occurrences and derive a model to assess their impact on the present and future forest yields; and 3) to develop a fire and disease risk factor growth and yield prediction model applicable over the boreal forest ecoregions.

STUDY AREA AND METHODS

BOREAL FOREST REGION

The boreal forest of North America extends as a continuous belt of predominantly coniferous trees from Newfoundland to the Rocky Mountains and Alaska (Rowe 1972). In western Canada, the boreal region is usually divided from south to north into three subregions (Maini 1968, Singh and Powell 1986):

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1. Forest-grassland transition: occupied primarily by trembling aspen (Populus tremuloides Michx.), willows (Salix spp.), snowberry (Symphoricarpos albus (L.) Blake), and grasses.

2. Predominantly forest: consisting mainly of white spruce (Picea glauca (Moench) Voss), black spruce (P. mariana (Mill.) B.S.P.), balsam fir (Abies balsamea (L.) Mill), jack pine (Pinus banksiana Lamb.), trembling aspen, and white birch (Betula papyrifera Marsh.).

3. Forest-tundra transition: consisting mostly of open-canopied white and black spruce stands, dwarf birch (Betula glandulosa Mich.), black crowberry (Empetrum nigrum L.), and lichens and mosses.

RISK FACTOR DATA

Development of the risk factor model for forest yield prediction was based on Alberta data. The McLeod Working Circle, in the leasehold of Champion Forest Products Ltd., was selected for the formulation and development of the model. The currently available data on risk factors and growth and yield were collated and examined through necessary data screening procedures. Historic data were retrieved from provincial records on fire and disease occurrences.

MODEL DEVELOPMENT

A total of 4 years was estimated to cover all stages of the study. The stages in the development of FOrestry RIsk Model (FORIM) include:

I. Initial stage: A review of risk and uncertainty factors in growth and yield due to fire and insect and disease occurrences, collection and evaluation of data relating to such factors.

II. Preliminary development stage: Preliminary attempts at development of a conceptual model dealing with risk factors relating to growth and yield.

III. Intermediary stage: Implementation of model concepts and strategies to achieve parameter estimation and calibration.

IV. Refinement stage: Improvement and refinement in risk factor model and parameter estimates to enhance model capabilities, and a validation test on independently collected and most recent data in a similar ecoregion in western Canada.

V. Final stage: Finalizing the risk factor model and its components for the boreal forest, and recommendations for its extention to disjunct outliers or ecoregions, including preparation of a manual for operational use and guidelines to prescribe needed management plans and timber harvesting strategies.

A work plan was devised for the expected 4 years of the study and goals were identified for each year according to the various stages described above.

PRELIMINARY VERSION OF MODEL (FORIM-1)

The work conducted under stages I and II during the current year includes preliminary development of the model under two main components: 1) forest yield prediction module, and 2) allowable cut module. As the names imply, the first module is to provide yield table information and the second module is to serve the planning requirements involved in annual alowable cut determination.

RESULTS AND DISCUSSION

FORIM-1 was produced through a contract under the Canada-Alberta Forest Resource Development Agreement (Dempsters and Stevens 1987). The main subroutines and tasks related to each are briefly described below for the major components.

FOREST YIELD PREDICTION

The input information and data needed for the model are read with the help of RDRUN, RDCOEF, RDAREA, and RDRISK subroutines (Fig. 1). These inputs are:

RDRUN - computer run parameters set during the execution of front-end of the program

RDCOEF - coefficients for height, site index, volume, years to stump, and breast height predictions

RDAREA - compartment area

RDRISK - probabilities of fire and insect and disease destruction

The subroutines used for computing and providing outputs are CALPO, GETAGE, SISRCH, HTCALC, VCALC, SUM, SUMPO, and YLDSUM. The tasks performed by these subroutines are:

CALPO - determines the cumulative probability of survival for fire and insect and disease risks

GETAGE - calculates breast height age

SISRCH - estimates site index from height and age

HTCALC - calculates vector of predicted heights from age at base date to end of projection period

VCALC - calculates volume from type and density under risk constraints

SUM - sums the vectors to provide precision estimates of volume at base age

SUMPO - calculates combined cumulative probability of survival and annual probability of destruction

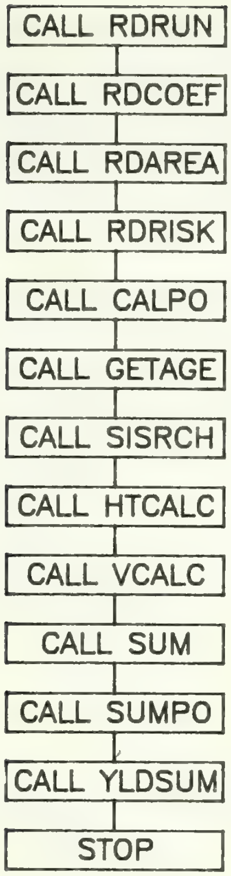

Fig. 1 Forest yield prediction subroutines

YLDSUM - summarizes the regeneration and fire-origin growth projections averaged over the plots

ANNUAL ALLOWABLE CUT COMPUTATION

The annual allowable cut module uses RDRUN and RDTAB subroutines to read input on run parameters and yield table information. Various required computations in this module are done by the following subroutines:

MANSEQ - Calculates the average of yield projections for subcompartments grouped together in a run sequence

MAXAGE - sorts compartments in descending order of age

AUTOSQ - automatically sequences compartments based on age

PROBAV - performs area/volume check by using maximum annual volume loss as a criterion for harvest compartments

GETCMP - determines which compartment will be cut first on the basis of maximum annual volume loss

AV - performs area-volume check

PRINT - prints required information

The choice of the subroutines to be used is made according to the type of run requested (Fig. 2).

RISK ANALYSIS OUTPUT

The fire rates used and the expected average annual yields under different rotations (80, 90, and 100 years) and fire severity classes are shown in Table 1. Absence of data on the reduction of growth rates and mortality caused by insect and disease infestations precluded the use of the model to assess these effects. On the basis of fire as a major risk factor, however, the results clearly showed that rotation length and fire risk severity have significant effect on annual forestry yields. The expected yields increased 8.3, 9.7, and 11.1% when rotation age was reduced by 10 years for mild, medium, and severe fire rates, respectively. Cumulative probability of realization of expected average annual yield is shown in Table 2. The range of risk involved increases with increase in rotation period.

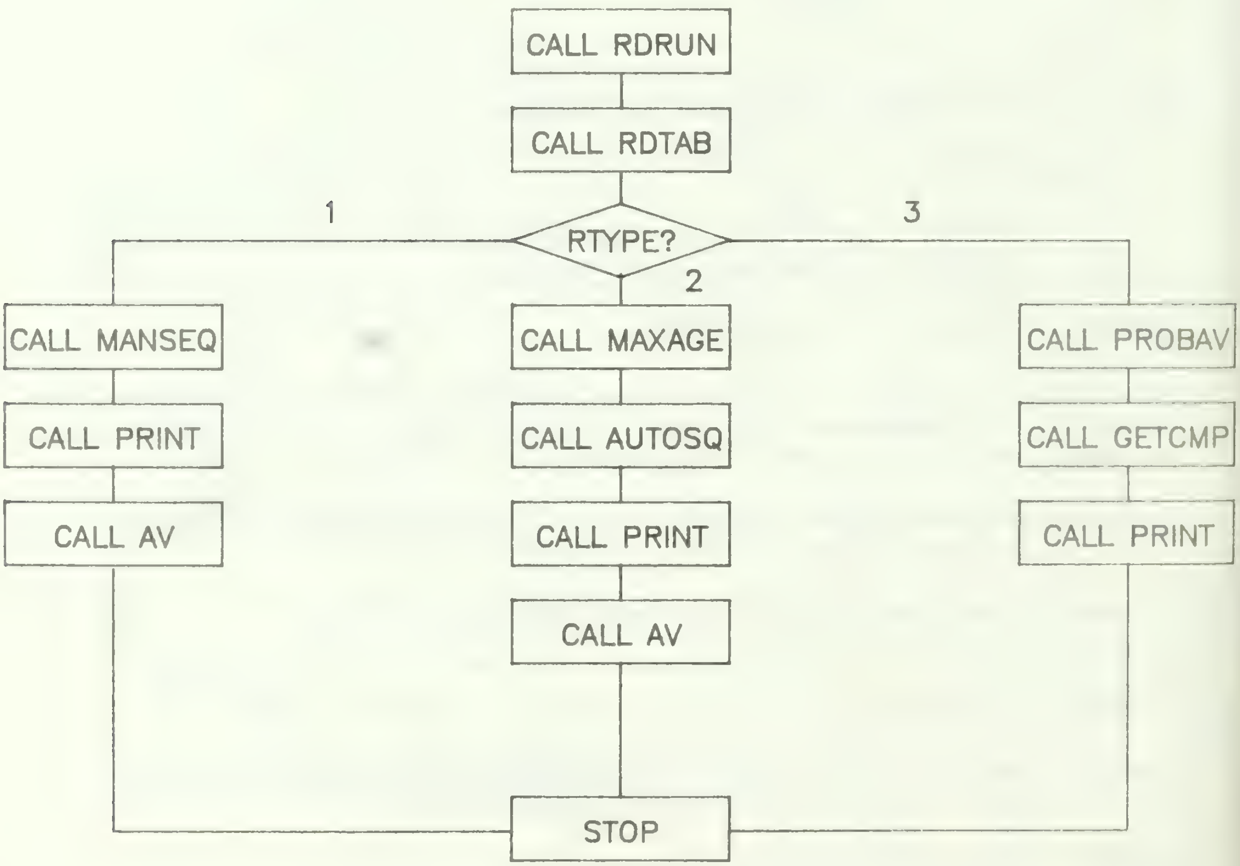

Fig. 2. Annual allowable cut subroutines.

Awareness of forestry risks and their adverse effects on forest growth and yield can play an increasingly important role in future management and prediction of timber supplies. Reducing rotation age and proper risk management have beneficial effects on expected annual yields. The preliminary work done on the risk factor model in this study holds promise for improved management and utilization of forestry resource in western Canada.

Table 1. Average annual yield (m^3) predicted by the risk factor model under historical boreal forest fire rates of Alberta

Fire Severity	Rotation (years)		
	80	90	100
1. Mild (0.26%)	361,551	335,519	305,214
2. Moderate (0.40%)	342,713	312,295	285,690
3. Severe (0.70%)	306,613	275,938	249,264

Table 2. Cumulative probability of realization of expected volume under different rotations and fire severity conditions.

Fire Severity	Rotation (years)		
	80	90	100
1. Mild (0.26%)	0.813-0.998	0.792-0.998	0.772-0.998
2. Moderate (0.40%)	0.727-0.997	0.699-0.997	0.671-0.997
3. Severe (0.70%)	0.572-0.995	0.534-0.995	0.497-0.994

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DETECTING EFFECTS OF STAND DYNAMICS WITH TREE RING DATA

Paul C. Van Deusen[1]

ABSTRACT. Although permanent plot data are preferred for studying the effects of stand dynamics, tree ring data may be all that are available. Some theoretical justification for using tree ring data to study stand dynamics is given along with two examples. Both examples presented here were motivated by allegations that atmospheric pollution is affecting forests, but no long-term data other than tree rings were available. The analytical techniques employed are based on graphical comparisons and the Kalman filter.

INTRODUCTION

The possibility that forest health is being threatened by air pollution is a relatively recent concern in the United States, and methods to quantify these effects in relation to some baseline will be needed. When the effects are severe, it may be obvious that the state of the forest has significantly deviated from a healthy baseline condition. However, subtle effects may be difficult to detect, particularly in the absence of a well defined baseline. The focus here will be on detecting effects, and the more difficult issue of associating the effect with a cause will be addressed marginally.

Two approaches to providing a baseline are involved. One approach is to compare groups of stands where the factor of interest is not believed to be present in one of the groups. In the example presented here, the factor is the occurrence of disturbance in the last century. The other approach is to use the stands own historical growth rate as a baseline for the current situation. Tree ring data are suitable for both approaches and were the only data available.

LITERATURE REVIEW

A partial list of publications expressing concern that an effect exists in forests within the United States demonstrates the difficulty of quantifying the effects and the extreme difficulty of attaching a cause to them. Sheffield et al. (1983) present evidence of a pine growth decline in the Southeastern United States. They suggest a number of potential causes for this, while others debate whether the effect exists at all (Lucier 1986). Red spruce (<u>Picea rubens</u> Sarg.) has been the subject of much concern about apparent growth declines. In the Northeast, Hornbeck and Smith (1985) have documented a synchronous decline in radial growth of red spruce from throughout the region.

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They suggest that one possible cause is stand maturation that was synchronized by logging and insect activity around 1915. Adams et al. (1985) present evidence of a radial growth decline in the mid-Appalachian subalpine forests and suggest that it may be due to a large scale environmental perturbation such as a change in air quality. McLaughlin (1985) gives a good review of the state of knowledge regarding effects of air pollution on forests.

It is clear from the citations above that the spector of forest decline has touched an extensive area of the Eastern United States. None of these allegations should be ignored or endorsed until available data are studied and statements made on this basis. However, political realities and the potential consequences of delaying action dictate that scientific understanding progress quickly. Tree ring data have potential for making timely progress in quantifying the effects at a reasonable cost.

BACKGROUND ON TREE RING ANALYSIS

Tree rings were first used as a tool to date Pueblo Indian structures in the Southwest. In 1929, the "Rosetta stone" log was discovered that matched a known tree ring chronology formed by A. E. Douglas, the father of dendrochronology. This log established that the pueblos were inhabited anywhere from the 10th to 13th centuries A.D. (Trefil 1985). The fact that rings can be crossdated between trees is the basis for all dendrochronological work that has developed since Douglas pioneered crossdating. Sequences of wide and narrow rings appear across all trees subject to the same regional influences, such as climate, and these can be matched to assure that all rings in a sample are assigned the proper date.

LINEAR AGGREGATE MODEL

Following crossdating, a conceptual model for ring width is needed as a basis for analysis. A linear aggregate model has been proposed (Graybill 1982) to describe the signals composing an individual tree ring, as follows:

$$R_{ijt} = B_{ijt} + D_{jt} + C_t + O_t + e_{ijt}, \qquad (1)$$

where R_{ijt} is the ring width of tree i in stand j at time t, B_{ijt} is the biological component for tree i in stand j at time t, D_{jt} is the stand level component at time t, C_t is the climate component at time t, O_t is a component for other disturbances at time t (say pollution or sunspots), and e_{ijt} is a catch-all for disturbances at the tree level that may be due to model errors, measurement errors, genetic factors, or local disturbances. Subscripts have been added to the usual linear aggregate model here to clarify the level at which the component operates.

Model (1) suggests that trees are affected by time varying factors and at least two spatial levels crossed with time. Spatially there is the individual tree level represented by the B and e components, and

second, the stand level represented by the D component. The purely time varying factors are represented by C and O. As the model is written, it appears that O and C are completely confounded. However, if the spatial influences of O and C are different, an additional subscript could be added and O and C could be separated. An example would be where O represents point source pollution and we have trees both in and out of the O-influence that are subjected to the same climate (e.g. Fox et al. 1986). This is a case where the spatial extent of O is much less than C.

STANDARDIZATION

The B and e components of model (1) are also difficult to separate, but dendrochronologists have done this by processes categorically referred to as standardization. The usual approach to standardization (Fritts 1976) is to fit a curve to the series R_{ijt}, $t=1,\ldots,T$ to obtain a predicted ring width for each time. Monserud (1986) motivates this procedure by pointing out that any ring width can be represented as a function of it's predicted value and an error term, thus

$$R_{ijt} = \hat{R}_{ijt} + e_{ijt}.$$

Assuming that e_{ijt} has zero mean and variance $\hat{R}_{ijt}\sigma^2$, the standardized index is

$$I_{ijt} = 1 + \frac{e_{ijt}}{\hat{R}_{ijt}} . \qquad (2)$$

Therefore, I_{ijt} has an expected value of 1, with a more homogeneous variance than the original series.

Rather than fitting a curve to the series and following the above procedure, it was assumed here that the tree ring width at some age, A_t, is described by a negative exponential with a random asymptote parameter, thus

$$R_{ijt} = b^{v_{ijt}} e^{-kA_t},$$

where $b^{v_{ijt}}$ is the random parameter. Assuming that v_{ijt} is a random walk process, i.e. $v_{ijt} = v_{ij,t-1} + a_{ijt}$ where a_{ijt} is white noise, the ring width can be standardized by first differencing the natural log of ring width:

$$\log R_{ijt} - \log R_{ij,t-1} = a_{ijt}(\log b) - k \quad . \qquad (3)$$

These assumptions lead to a standardized series, as do the more usual assumptions. For those who do not like the exponential assumptions, another justification for equation (3) is that taking the logarithm puts the ring widths on a common relative scale, and first differences are just numerical first derivatives. Thus, taking the first difference of the log of ring width results in a relative growth rate variable, and that is basically what one hopes to achieve with standardization regardless of how it is performed. All analyses described here were based on data transformed as in equation (3).

COMPARING TWO STAND TYPES

Hornbeck and Smith (1985) suggested that second-growth red spruce in the Northeastern United States shows reduced growth due to stand dynamics resulting from past logging and insect activity. Van Deusen (1987a) compared proximate old-growth stands with the Hornbeck and Smith (1985) data in an effort to verify the stand dynamics hypothesis. The alternative hypothesis -- that some large scale atmospheric or climatic change had occurred -- seemed plausible because the Hornbeck and Smith (1985) data came from throughout the red spruce zone in the Northeast. Therefore, it is important to test the stand dynamics hypothesis if possible.

A graphical approach and a modelling approach based on the Kalman filter were used in Van Deusen (1987a), but only a subset of the graphical results is presented here (Figure 1). Chronologies were formed by transforming the ring widths as in equation (3) and averaging for each year within each data set. The chronologies are presented (Figure 1) with the second-growth data set on the left being matched with the most proximate old-growth data set on the right. Hopefully, all components in model (1) are similar for these matched pairs except the stand level component, D_{ij}.

Careful inspection of the second-growth stand chronologies (Figure 1) shows that these average relative growth rates tended to be positive from 1900 to 1950 and then tended to be negative. If stand dynamics was not the cause for this effect, then the old-growth stands should also show the same trend. The old-growth stands mostly show a consistent, nondescript trend that implies they were not responding to the same cause as the second-growth stands. One can argue that these data sets are not well matched, but I believe this comparison supports the stand dynamics hypothesis.

DETECTING SUBTLE DISTURBANCE EFFECTS

Examining ring width data graphically (Figure 1) or otherwise may reveal long-term growth trends. However, there may be cases where the effect is not apparent by examining the ring widths alone. For example, the sensitivity of the ring widths to some aspect of climate may change subtlely over time. This could be due to stand level disturbances from insects or logging, or theoretically, from the imposition of a new atmospheric influence that would distort previous relationships.

Atmospheric pollution or "greenhouse" effects are likely to be subtle at first, and methods are needed for early detection. The Kalman filter is proving to be a useful analytical technique for detecting subtle effects in tree rings (Van Deusen 1987b, Visser and Molenaar 1987). As the name implies, the Kalman filter is able to filter a signal out of noisy data. A brief description of the Kalman filter is given below, followed by an example in which a subtle shift in climate sensitivity was detected in tree ring data from the Smoky Mountains.

THE KALMAN FILTER

The Kalman filter provides a method for estimating over time an unobservable random variable or state parameter, X_t, from an observable random variable, Y_t, where X_t and Y_t can be related by a linear dynamic system of equations. The observation equation relates Y_t and X_t, thus

$$Y_t = F_t X_t + v_t,$$

where Y_t is an n_tx1 vector of tree ring data at time t for our purposes, F_t is a fixed $n_t$xp matrix, n_t is the sample size at time t, X_t is a px1 vector of state parameters, and v_t is an n_tx1 vector of residuals with zero expectation and variance matrix V_t. The transition equation allows X_t to evolve over time as a first order Markov process, thus

$$X_t = G_t X_{t-1} + w_t,$$

where G_t is a fixed pxp matrix, and w_t is a px1 vector of residuals with zero expectation and variance matrix W_t. The equations giving the optimal solution to the problem of estimating X_t are well known (Jazwinski 1970, Harvey 1981).

DETECTING CLIMATE SENSITIVITY CHANGE

The red spruce-Fraser fir (*Abies fraseri*) ecosystem of the Smoky Mountains is showing signs of decline (Adams et al. 1985), and a number of unconfirmed hypotheses about the cause exist (McLaughlin 1985). The situation is particularly difficult to study because of insect damage from *Adelges piceae*, which primarily attacks the fir component, leaving the residual spruce stand in a disturbed state. Thus, it is difficult to separate insect damage from other potential causes such as climatic change.

This disturbed situation provides an opportunity to examine the power of the Kalman filter to detect differential response to climate over time. The Tree-Ring Laboratory of the Lamont-Doherty Geological Observatory (E. R. Cook pers. comm.) provided a data set for this analysis consisting of 2 cores from each of 17 red spruce trees on Clingman's Dome in the southern Appalachians. A Kalman filter was set up to study these data as follows:

Observation equation $$Y_t = F_t \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} + v_t \qquad (4a)$$

Transition equation $$\begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} = \begin{bmatrix} C_t x_{2,t-1} \\ x_{2,t-1} \end{bmatrix} + \begin{bmatrix} w_{1t} \\ w_{2t} \end{bmatrix}, \qquad (4b)$$

where C_t is a principal components linear combination of monthly average temperature and total rainfall as described in Van Deusen

(1987b). The variance matrices were assumed to be

$$V_t = \sigma_t^2 I_t, \text{ and}$$

$$W_t = \frac{\sigma_t^2}{n} \begin{bmatrix} 1 & 0 \\ 0 & q \end{bmatrix}, \text{ where}$$

$$\sigma_t^2 = \frac{\sum_i \left[\Delta \log R_{it} - \overline{\Delta \log R_t} \right]^2}{(n_t - 1)},$$

I_t is an identity matrix of order n_t, and q is estimated using maximum likelihood as described in Harvey (1981). The value of q for this example was approximately 0.012. Greater detail on this Kalman filter approach can be found in Van Deusen (1987b).

The parameter x_{2t} in equation (4b) represents the sensitivity of the standardized ring widths to climate over time. The x_{1t} parameter is analogous to an average chronology and will equal one-half the average chronology when the climate variable is set to zero (Van Deusen 1987b). The results of applying equations (4a) and (4b) to the Southern red spruce data are presented in graphical form (Figure 2). No trend is evident in the x_1 parameter (Figure 2a), but the climate sensitivity parameter, x_2, (Figure 2b) shows an obvious trend over time. Approximate 95-percent confidence intervals are given about the x_2 parameter by dashed lines. Beginning in 1920, the sensitivity to climate increases and then disappears shortly after 1945. The sensitivity to climate then becomes significantly positive after 1970 and continues until the data end in 1983. It is not possible to conclusively attach a cause to these effects, but one might speculate that the 1920-1945 sensitivity was due to logging or some other disturbance that occured around 1920, and the more recent increasing sensitivity has been due to insect caused thinning of the fir component in these stands. Apparently, the confidence interval is widening in the 1980's, which may portend a breakdown in this historical climate relationship.

CONCLUSIONS

Trees in temperate zones are a natural data storage mechanism that can provide long-term historical records in areas where no other data source may be available. Two uses of tree rings have been presented that yield additional information about red spruce forests allegedly showing decline symptoms. Neither of these examples results in indisputable conclusions, but it is fair to say that additional insight was gained in a timely and inexpensive manner.

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FIGURE 1. Chronologies of second-growth red spruce (left side) and old-growth red spruce (right side) for comparison.

(a)

(b)

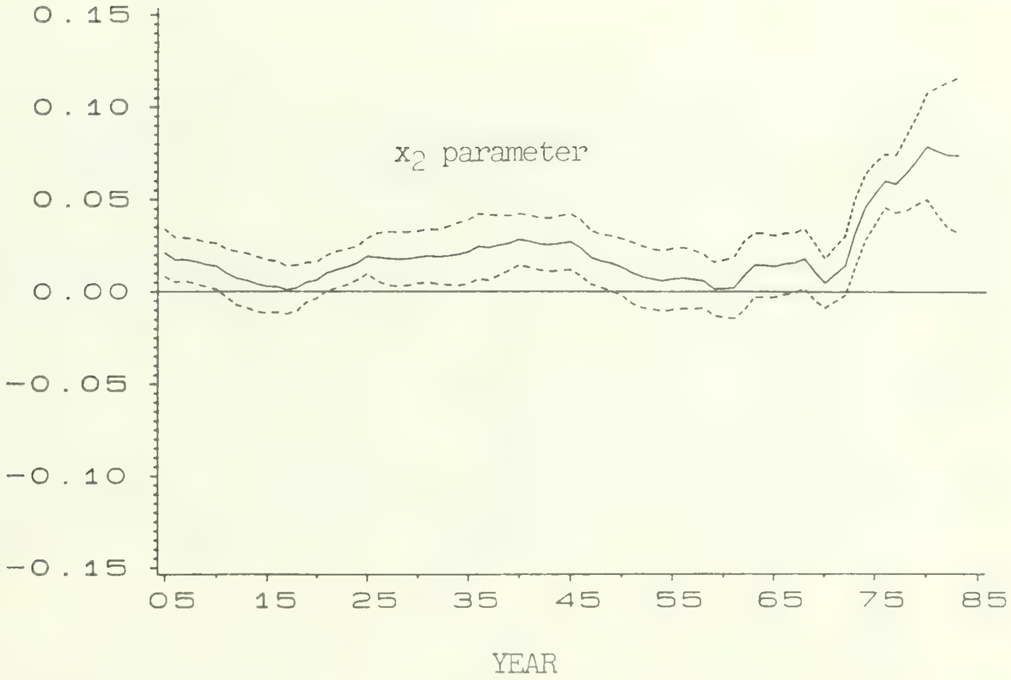

FIGURE 2. Plots of the x_1 and x_2 parameters described in equations 4a and 4b. Plot b represents the sensitivity to climate over time of red spruce in the Southern Appalachians. Year range of data, 1905-83.

MODELLING THE EFFECTS OF AIR POLLUTION ON FOREST PRODUCTIVITY:

A SENSITIVITY ANALYSIS USING PTAEDA

Charles D. Webb and Harold E. Burkhart[1]

ABSTRACT. As part of planning research on the effects of air quality on forest productivity, a sensitivity analysis was conducted using PTAEDA2, a loblolly pine growth and yield model. The objective was to simulate pollution-caused growth reductions of varying intensities on varying proportions of the stand to determine how severe impacts must be before there is an appreciable change in volume per acre. Before total volume per acre was reduced appreciably, more than half the trees in the stand had to be impacted, unless the annual impact on affected trees was very severe. When the growth loss was assigned to the tallest trees each year, there was generally a greater effect on total volume per acre. To develop models adequate for simulating effects of air pollution on stands, data should be gathered on mature stands defining proportions of individuals tolerant and susceptible to air pollution; competition measures should be devised to adequately account for pollution effects; and crown functions should be developed which accurately reflect pollution impacts on photosynthetic area and efficiency.

INTRODUCTION

In recent years, concern has grown in North America that forest productivity in certain areas has declined as a result of air pollution and that trends are similar to those developing in Europe. The National Council of the Paper Industry for Air and Stream Improvement (NCASI) initiated a research program to determine whether air pollution is impacting the productivity of commercial forests. As part of the NCASI research planning process, a sensitivity trial was initiated with the loblolly pine (Pinus taeda L.) growth model, PTAEDA2. The objective was to simulate pollution-caused growth reductions of varying intensities on varying proportions of the stand to determine how severe impacts must be before there is an appreciable change in volume per acre.

It has been hypothesized that ambient levels of air pollution affect the productivity of forests by changing the physiological processes of individual trees---some more than others---and by changing the productivity of the soil and the dynamics of soil-borne organisms. However, to date

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there is little credible scientific data on regional air pollution effects on forest productivity, and the data that do exist are largely on seedlings, not stands of trees. The primary question is: "What is the stand-level impact of air pollution on forest productivity, if any?"

Stands of trees are complex ecosystems with numerous interactions between the individual members. The stand-level impact of growth suppression of individuals depends upon the proportion of individuals affected, the severity of the effect, the age(s) at which the effect occurs, the stocking level of the stand, the site quality of the land and other related factors.

PROCEDURES

SELECTION OF STAND MODEL

An early version of the loblolly pine plantation model PTAEDA2 (Burkhart et al., 1987) was used in this study. This model was selected because (1) as an individual-tree distance-dependant model, it takes into account trees and their interactions when predicting stand growth, (2) it is based on an accepted model framework (Daniels and Burkhart, 1975), (3) it is calibrated for loblolly pine plantations on cutover sites with a large data set from throughout the Southeastern United States, and (4) loblolly pine is a commercial species of paramount importance in southern pine plantation management.

SELECTION OF IMPACTED TREES AND AGES

Definitive data are not available on the degree of growth loss that mature, forest-grown trees experience as a result of air pollution. Therefore, changes in growth were implied based upon interpretation of trends reported in the literature.

Two different procedures were followed to specify which individual trees in the simulated stand were affected:

1. Random selection:--In European forests, it is a well-established phenomenon for a tree, apparently undamaged by air pollution, to be growing in a mature forest next to trees showing severe damage symptoms (Scholz and Bergmann, 1984). Furthermore, an appreciable part of this variation is under genetic control (Houston and Stairs,1973; Mejnartowicz,1984). Based on these reports, a completely random impact scenario was assumed to simulate genetic variation in susceptibility/ tolerance.

2. Tallest-trees-first:--European experience also suggests that trees growing in exposed positions suffer greater damage, because they presumably receive greater quantities of pollutant and more intense sunlight (Institute for Forestry Experimentation and Research, 1984). From this, a different impact scenario was inferred: it was assumed that the tallest trees in a fully stocked stand were more exposed to pollutants. Therefore, reductions were allocated to the tallest trees at each year of the simulation period. This assumes that impact is determined solely by position in the canopy and that all trees, regardless of genotype, will be impacted if they are in the taller stand component.

Height and diameter increment were impacted annually after the 10th growing season, and impacting continued through the 30th growing season (i.e., stands were impacted for 20 years). In the case of random selection, growth of the selected trees was modified each year until they died or the end of the simulation was reached. When the tallest portion was impacted, the specified percentage of the tallest live trees was identified at the end of each growing season and that group of trees was impacted the next growing season. A constant proportion, but a decreasing number of trees through time, was impacted with this scenario.

SPECIFICATION OF PROPORTION IMPACTED

Unfortunately, little guidance was available from the literature on variation in response to air pollution within populations of loblolly pine. Although dose-response results on loblolly seedlings from 100 half-sib families will soon be available, nothing is known about the frequencies of individuals tolerant of air pollution and those susceptible under forest stand conditions. Therefore, a range of values was specified, based upon subjective assessment.

COMBINATIONS OF VARIABLES SIMULATED

The following variables were studied and the impact on the final estimated stand yield ascertained:

Proportions of population impacted:
10 %   20%   40%   80%

Annual impacts on diameter and height increment of susceptible trees:
-1%   -2%   -4%   -8%   -25%   -50%.

Since both diameter (D) and height (H) increment were reduced, volume increment was reduced to a greater degree. For example, assuming individual tree volume is proportional to D^2H, an 8 % reduction in both diameter and height increment will produce a reduction in volume increment of approximately 22 %.

No modifications to mortality were made. It was assumed that modifications in height and diameter would translate through the model in the form of appropriate modifications in mortality.

SITE AND STOCKING CONDITIONS SIMULATED

A range of site qualities and stand densities was evaluated: low (site index 50 feet, base age 25 years), medium (site index 60) and high (site index 70); low (300-400 trees/acre), medium (680-800 trees/acre) and high (more than 800 trees/acre) numbers of trees planted.

Although modifying the height/age function could have been used to simulate hypothesized changes in soil productivity, that was not attempted in this study. The combinations tested approximate the effects that might accrue from gaseous pollutants and acid deposition effects through the foliage.

NUMBER OF REPETITIONS

PTAEDA2 has stochastic elements and thus a different answer is obtained for each different random number seed. Several runs can be made and the results averaged to establish mean trends. In the simulations for the random selection of trees, three runs of a 100-tree simulation plot were averaged. For the tallest-trees-first cases, a single run of a relatively large simulation plot (225 trees) was used. However, due to the vagaries of random numbers, all trends will not be perfectly smooth.

RESULTS AND DISCUSSION

Simulations showed similar trends for low (site index 50), medium (site index 60) and high (site index 70) quality sites. Likewise, low (300-400 trees/acre), medium (680-800 trees/acre) and high (more than 800 trees/acre) numbers of trees planted showed similar trends. Consequently, only the case of site index 60 with 800 trees per acre planted will be discussed here.

Figure 1 shows a summary of impact values for total cubic-foot volume per acre at age 30, site index 60, 800 trees per acre planted with percent trees impacted of 10, 20, 40 and 80 and annual impacts of -2, -4, -8, -25 and -50 percent. Table 1 contrasts growth suppression for trees randomly selected and the "tallest-trees-first" scenario, for annual growth reductions of - 8 %, - 25 % and - 50 %.

Several trends are evident:

1. At the lower annual growth reduction levels, there is relatively little impact on per acre yield when less than half of the stand is affected. This seems reasonable since approximately half of the original trees planted will be removed as a result of mortality in a 30-year rotation.
2. Loss of height and diameter increment of less than 10 % per year on a portion of individuals probably would be un-detected in a normal forest ecosystem.
3. For air pollution to significantly reduce yield per acre, more than half the trees in the stand would have to be impacted, unless individual-tree growth loss is quite severe.
4. In general, impacting the tallest portion of the stand has a larger effect on yield than randomly selecting the trees to be impacted. This trend is expected.

In the model there is a certain amount of "self compensation." If the neighbors of a subject tree are smaller, the competition index is reduced and the subject tree grows faster. Although all trees may be reduced in height and diameter growth, a certain amount of that reduction is compensated for by increased growth the following simulated growing season. Whether or not this behavior is reasonable for pollution effects is unknown. If the overall carrying capacity of the site is reduced by pollution, then the model probably over-compensates. Reduced growth potential or carrying capacity could be incorporated into growth and yield models if such reductions were established as being biologically reasonable and expected.

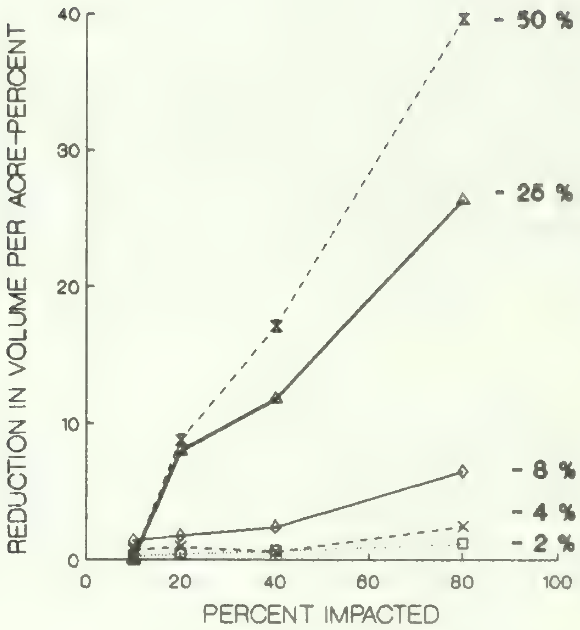

Figure 1. Reductions in volume per acre at age 30 for various annual reductions in height and diameter increment and various proportions of the population impacted by "Random selection".

Table 1. Reduction in volume per acre by "Tallest-trees-first" compared with "Random selection" for various annual reductions in height and diameter increment and various proportions of the population impacted.

Percent Impacted	Annual impact on D and H Percent	Reductions in volume by method of selection: Tallest	Random
		--------Percent-------	
10	- 8	- 2.85	- 1.43
	- 25	- 8.17	0.45
	- 50	-15.1	0.45
20	- 8	- 3.94	- 1.73
	- 25	-10.5	- 7.9
	- 50	-20.9	- 8.7
40	- 8	- 4.21	- 2.42
	- 25	-17.8	-11.8
	- 50	-32.2	-17.1
80	- 8	- 9.31	- 6.46
	- 25	-25.7	-26.4
	- 50	-47.4	-39.6

Another possible way to modify tree, and consequently stand, growth would be to modify the crown variable directly. Modification of one of the independent variables while holding all others constant is not entirely legitimate, however, unless the independent variables are orthogonal. The simulations reported here used a prototype of the PTAEDA2 model in which the modifier function for height increment involved crown ratio, but the modifier function for diameter increment used crown length. Response surface diagrams were drawn of the modifier portion of the height and diameter increment equations. These graphs showed that height increment responds reasonably to changes in crown ratio. In contrast, diameter increment was "flat" (unresponsive) to crown length changes but steep (highly responsive) to changes in competition index. Apparently crown length and competition index are highly correlated and changes in competition index also reflect changes in crown length. The modifier function in the diameter increment equation was respecified and refitted with crown ratio as the measure of tree vigor. This is the form used in the published version of the PTAEDA2 model. This equation (with crown ratio as a predictor variable) showed much greater sensitivity to changes in crown dimensions. When this modifier function is employed, direct modification of crown ratio would probably give reasonable results.

Not only must model specification be considered, but the structure of the data used to estimate the coefficients must be considered as well when devising methods for modifying models to reflect external forces such as air pollution impact. No single method will necessarily work in all instances with all models. A great deal of "art" will likely be required to come up with a workable solution, and the procedures followed must be documented carefully!

FUTURE RESEARCH NEEDS

A key factor appears to be whether or not all trees in a stand are affected to some degree by pollution, or whether some trees are impacted but some trees remain tolerant. If enough trees are tolerant, they can compensate for the growth loss on trees which are affected, and volume per acre remains relatively unchanged. If all trees are affected to some degree, some more than others, then there is a chance that productivity per acre will be reduced. Therefore, future dose-response studies should be designed to define the responses of populations to varying levels of pollutants.

The scenarios examined to date are admittedly simplistic. One would not expect a dichotomy with some trees susceptible to air pollution impact and others not. In all likelihood a continuum of susceptibility exists. The distribution of susceptibility to air pollution in "natural" populations of loblolly pine stands is, however, not known. Nevertheless, these simulations do illustrate that a sizeable portion of the population must be impacted at a reasonably high level before significant per acre yield reductions are likely to occur. Whether or not other models for loblolly pine would give similar results has not been explored.

If exposed trees, dominants and co-dominants, actually do sustain greater damage from pollutants than protected trees, intermediates and suppressed, then productivity on a unit-area basis may be significantly reduced. Therefore, studies are needed to determine whether exposed trees actually suffer greater growth losses and why.

Results from dose-response studies must be properly incorporated into stand models to obtain meaningful estimates of per acre impacts from air pollution. Currently available models like PTAEDA2 show promise for this incorporation, but a great deal of finesse will be required.

Another option would be to construct a stand model specifically for estimating impact from air pollution. Since air pollution affects the physiology of tree crowns and accelerates foliage loss, a more appropriate model would use more detailed foliage variables than the simple crown length measures used in most past studies. An approach similar to that followed by Mitchell (1975) in his Douglas-fir model should prove useful. In Mitchell's approach, foliage volume by age class is computed. Each age class is assigned a photosynthetic efficiency and a retention rate. The weighted foliage amount (weighted by photosynthetic efficiency times retention rate) and a competition index could be related to tree height and diameter increment. Such a model could more directly and easily incorporate results from dose-response studies than models that do not employ detailed foliage variables.

To summarize, from these preliminary results, we conclude that the following information would contribute significantly to attempts to estimate the effects of air pollution at the stand level:

1. Quantitative data on the proportion of the population tolerant of air pollution, the proportion susceptible, and the variation in severity of impact among the susceptible trees to specified exposure regimens, at different ages.

2. The degree of interaction between exposure response and competition with neighbors.

3. Crown functions that can represent changes in (a) altered physiological processes in the foliage as a result of air pollution and (b) reductions in photosynthetic area (i.e. needle-drop).

4. Data on the role of relative exposure of individual trees (dominants vs. co-dominants, and intermediates) on the degree of damage.

5. Dose-response functions for trees, not seedlings, that express the effects of air pollution on various aspects of tree growth, above and below ground.

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COMPATIBLE MODELS FOR SURVIVAL, BASAL AREA GROWTH, AND DIAMETER DISTRIBUTIONS OF FERTILIZED SLASH PINE PLANTATIONS

Robert L. Bailey and J. A. Aleixo da Silva[1]

ABSTRACT. Changes in basal area, trees per acre and diameter distributions consistent with them are predicted using models derived from a system of differential equations. The equations, fitted with data from 263 plots in fertilized and unfertilized slash pine plantations, include N and P fertilization rates and soil groups as predictor variables. Fertilization did not affect mortality but did affect basal area growth. A novel technique for imposing boundary constraints on predicted values from a regression is presented and a new method of applying the Weibull distribution is developed.

INTRODUCTION

Slash pine (*Pinus elliottii* var.*elliottii* Engelm.) is one of the two most widely used species for reforestation in the Lower Coastal Plain of the Southeastern U. S., accounting for 12% of the total volume of pine growing stock. The slash pine ecosystem totals about 12.8 million acres; 52% are plantations (Sheffield et al. 1981). Starting in the early sixties, fertilization of these plantations became an operational practice. Recently, fertilization to accelerate growth of mid-rotation stands for the production of solid wood products has become common practice (CRIFF 1984). To date, no satisfactory growth and yield prediction models have been developed to help managers evaluate the economic returns from this investment. Analyses have primarily focussed on treatment effects rather than on modeling growth.

Our study investigates fertilization growth responses in mid-rotation (ages 10 to 20) slash pine plantations. Survival, basal area growth, and diameter distributions are modeled. The integrated system of prediction equations is used to predict changes in stand density and diameter distributions following nitrogen and phosphorus fertilization. A technique for imposing boundary constraints on regression models is developed in order to obtain a basal area growth equation which will only predict non-negative fertilization responses.

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STUDY DESCRIPTION

In 1973, the Cooperative Research in Forest Fertilization Program (CRIFF, University of Florida) started a project in which one of the goals was to determine yield response of established stands of slash pine to rates and ratios of N, P and other essential elements over a wide range of lower Coastal Plain soils, stand ages, site qualities and stocking conditions. Selected stands had to be located in the Lower Coastal Plain and be between 9 and 23 years of age since planting. Old field sites were excluded unless a cooperator had no site-prepared plantation meeting all other requirements. Thinned stands were excluded and the basal area had to be less than 125 ft^2/ac at the time of study establishment. All the plots for any one test area had to be located within the same stand, having the same soil type.

Treatment plots (gross plots) were seven rows wide (trees spaced 8 by 10 ft) by 100 ft long. Two buffer rows on each side and a buffer zone of 15 ft at either end defined the net plot. All trees in the net plot were numbered and measured at the time of fertilization and 3, 5, 8, and 10 years later. The source of fertilizers applied were urea and concentrated superphosphate. Two levels of P (zero and 100 lbs/ac) were applied in combination with four levels (zero, 100, 200 and 400 lbs/ac) of nitrogen.

Treatments were applied in a randomized complete block design replicated three times at each of eleven locations. The distribution of the individual tests by location and CRIFF soil group (Munson 1984) is as follows:

Test	Location	Initial age	Soil group
B150	Chatham Co.,Ga.	15	B
B201	Wayne Co.,Ga.	10	B
B202	Wayne Co.,Ga.	16	D
B209	Long Co.,Ga.	14	B
B211	Nassau Co.,Ga.	16	D
B219	Baldwin Co.,Al.	15	E
B220	Calhoun Co.,Fl.	9	B
B221	Nassau Co.,Fl.	15	D
B224	Hamilton Co.,Fl.	9	C
B227	Gulf Co.,Fl.	13	A
B230	Madison Co.,Fl.	13	G

Excessively high mortality in one plot due to mechanical damage made those data incongruous, so the analyses are based on data from 263 plots.

ANALYSIS OF RATES OF CHANGE

Compound rates of mortality and basal area growth were calculated for every combination of soil group, initial age, and level of fertilization using the formula:

$$r=(Y_2/Y_1)^{\{1/(A_2-A_1)\}}-1 \qquad (1)$$

where Y_i is either trees per acre or basal area at age A_i.

An analysis of variance was performed with the r values from equation (1) based on a nested experimental design. Fertilization did not significantly affect mortality but did affect basal area growth rate (Table 1).

TABLE 1. Analysis of variance for rates of change in trees per acre and basal area.

Source	df	Rate of change tested	
		Trees/ac	Basal area
		--Probability level for test --	
Soils	5	0.0001	0.0001
Age(Soils)	4	0.0001	0.0001
Fert.	7	0.5695	0.0001
Fert.*Soils	35	0.4900	0.0001
F*A(Soils)	28	0.4371	0.9827
Residual	183		
Total	262		

SURVIVAL

Da Silva (1986) developed a differential equation relating trees/ac ($\mathbf{T}$) to age ($\mathbf{A}$),

$$\frac{\partial T}{\partial A} = \theta_1 T \theta_2^{A} \tag{2}$$

which, when solved, gives the projection equation

$$T_2 = T_1 \exp\{ \varphi(\theta_2^{A_2} - \theta_2^{A_1})\} \tag{3}$$

where $\varphi = \theta_1/\ln\theta_2$. In equation (3), T_i is the number of trees per acre at age A_i and the θ_i's are parameters to be estimated. Equation (3) was easily fitted with nonlinear least squares (Da Silva 1986), and only parameter estimates with asymptotic 95% confidence intervals which excluded zero were retained. Zero-one dummy variables (Z_j's) were used to represent soil groups, the final model is

$$T_2 = T_1 \exp\{ -0.00179(\hat{\theta}_2^{A_2} - \hat{\theta}_2^{A_1}) \tag{4}$$

where $\hat{\theta}_2 = 1.22647 - 0.073396Z_A - 0.046942Z_D - 0.015329Z_E$, and $Z_j = 1$ if the trees are in soil group j, $Z_j = 0$ otherwise. This model explains 96% of the variation about the mean value of T_2. Base-age-25 site index was not a significant variable after soil groups were included in the model.

BASAL AREA GROWTH

For basal area growth, we chose the differential equation on which Clutter's(1963) basal area model is based:

$$\frac{\partial B}{\partial A} = A^{-1} B[\Phi - \ln\{B\}] \tag{5}$$

The variables are basal area ($\mathbf{B}$) and age ($\mathbf{A}$), and the parameter Φ is independent of them. In previous applications of this model, Φ was a function of site index. The solution to (5) gives the projection equation

$$\ln\{B_2\} = \left(\frac{A_1}{A_2}\right)\ln\{B_1\} + \Phi\left(1 - \frac{A_1}{A_2}\right) \tag{6}$$

where $\mathbf{B_i}$ is basal area at age $\mathbf{A_i}$. With stepwise regression on the log-linear form of (6) and plotting of Mallow's C_p, we developed the following linear equation for Φ:

$$\Phi = \beta_0 + \beta_1 A_f + \beta_2 N + \beta_3 N^2 + \beta_4 N B_f + \beta_5 Z_B + \beta_6 Z_C + \beta_7 Z_D + \beta_8 Z_E + \beta_9 P Z_A + \beta_{10} P Z_B + \beta_{11} P Z_D \tag{7}$$

where the $\mathbf{Z_j}$'s are as defined for (4) above; $\mathbf{N}$ and $\mathbf{P}$ are lbs/ac of nitrogen and phosphorus respectively; $\mathbf{A_f}$ and $\mathbf{B_f}$ are the age and basal area at the time of fertilization.

When the exponential form of (6) with Φ defined by (7) was fitted with nonlinear least squares, negative responses to fertilization were predicted for some combinations of soil group and fertilization. Even though such an effect may be possible, a study of the cell means for the data refutes it. The problem was caused by $\beta_1 - \beta_4$, so these four terms were used to define $\Lambda = \beta_1 A_f + \beta_2 N + \beta_3 N^2 + \beta_4 N B_f$. Then, using the absolute value function, $|\Lambda|$, Φ was redefined as

$$\Phi = \frac{(|\Lambda| + \Lambda)}{2} + \beta_0 + \beta_5 Z_B + \beta_6 Z_C + \beta_7 Z_D + \beta_8 Z_E + \beta_9 P Z_A + \beta_{10} P Z_B + \beta_{11} P Z_D \tag{8}$$

The first term in (8) will always be either positive or zero and, as a function of N, it will inflect only once.

When (7) was replaced by (8), the estimates for $\beta_5 - \beta_{11}$ were all positive (Table 2). None of the 95% asymptotic confidence intervals for the parameter estimates included zero, and the model with these estimates explained 90% of the observed variation in $\mathbf{B_2}$ about its grand mean. Site index was not a significant variable after including soil groups. The interaction effects discovered in the analysis of variance of growth rates are reflected in this model. The 13:1 magnitude of the estimate for β_9 in comparison to those for β_{10} and β_{11} indicates the importance of fertilizing soils in group $\mathbf{A}$ with phosphate. Plantations growing in those soils show little response to added nitrogen but show tremendous increases in growth rates due to the addition of phosphate.

In fitting (6), all observed growth intervals, even overlapping intervals, were used. We believe this allows a maximum of information on growth to be included in the estimation process and gives more reliable predictions for differing lengths of growth period. In order to account for the

system of seemingly unrelated regressions, one for each period length. In another paper given at this same meeting, B. E. Borders *et al.* give the details of this approach for fitting projection models to data from remeasured plots.

TABLE 2. Parameter estimates for the basal area model, equation (6), with Φ defined as in equation (8).

Equation term (i)	Variable	Parameter estimate ($\hat{\beta}_i$)
0	Constant	4.8036
1	A_f	-0.04567
2	N	0.006096
3	N^2	-0.9344E-5
4	NB_f	-0.8816E-5
5	Z_B	0.64387
6	Z_C	0.73290
7	Z_D	0.53232
8	Z_E	0.53356
9	PZ_A	0.017049
10	PZ_B	0.0013378
11	PZ_D	0.0012524

DIAMETER DISTRIBUTIONS

A useful model for diameter distributions is the Weibull function:

$$F(y) = 1 - \exp\{-[(y-\alpha)/\beta]^{\chi}\} \tag{9}$$

where y=dbh, α=the smallest possible dbh, β is a scale parameter, χ is the shaping parameter, and $F(y)$ gives the proportion of the total number of trees less than or equal to y.

Several authors have developed diameter distribution models using percentiles. Our model is based on equations to predict the 0^{th} (minimum dbh), 25^{th}, 50^{th}, and 95^{th} percentiles of the Weibull. We developed the projection equation:

$$P_{i2} = P_{i1} + \theta\{D_2^2 \mu^{A_2} - D_1^2 \mu^{A_1}\} \tag{10}$$

where P_{ij} and D_j are the i^{th} percentile and the quadratic mean diameter, respectively, at age A_j (i=0,25,50,95;j=1,2). Equation (10) is compatible with the differential equation

$$\frac{\partial P_i}{\partial A} = \xi_0 \mu^A \left\{ \xi_1 D^2 + \xi_2 \left(\frac{\partial D^2}{\partial A} \right) \right\} \tag{11}$$

Since equations (4) and (6) jointly provide a method for predicting D_2, the quadratic mean dbh at age A_2, equation (10) can be written as a function of basal area (B_1) and trees per acre (T_1) at age A_1,

$$P_{i2} = P_{i1} + \theta\left(\frac{B_1}{T_1}\right)\left[\hat{\tau} B_1^{(A_1/A_2-1)} \mu^{A_2} - \mu^{A_1}\right] \tag{12}$$

where

$$\hat{\tau} = \exp\{\hat{\Phi}(1 - A_1/A_2) - \hat{\varphi}(\hat{\theta}_2^{A_2} - \hat{\theta}_2^{A_1})\} \tag{13}$$

In equation (13), the estimates $\hat{\varphi}$ and $\hat{\theta}_2$ are from (4) and $\hat{\Phi}$ is from (8). Equation (12) was fitted with nonlinear least squares to obtain estimates for θ and μ (Table 3). None of the asymptotic 95% confidence intervals for these eight parameter estimates included zero.

TABLE 3. Parameter estimates and percent variation explained for equation (12) as applied to four percentiles.

Percentile	$\hat{\theta}$	$\hat{\mu}$	Variation explained (%)
0^{th}	-1199.384	0.65807	85
25^{th}	-1251.794	0.68706	92
50^{th}	-1189.935	0.70748	93
95^{th}	-1282.871	0.72958	92

To obtain Weibull parameters from basal area, trees per acre and the percentiles, we applied the equation for the expected value of the minimum observation from a sample of size n,

$$P_0 = \alpha + (\beta / n^{1/\chi})\Gamma_1 \tag{14}$$

where $\Gamma_k = \int_0^\infty t^{(k/\chi)} e^{-t} dt$ is Euler's integral (i.e., the gamma function).

Making the assumption that χ = 3.0, the 50^{th} percentile

$$P_{50} = \alpha + \beta[-\ln\{0.5\}]^{1/\chi} \tag{15}$$

and equation (14) can be solved simultaneously to give

$$\hat{\alpha} = (n^{1/3} P_0 - P_{50})/(n^{1/3} - 1) \tag{16}$$

Within the usual range of values for χ, the above estimate for α is quite reliable. To use the models when plot size is unknown, trees per acre should be multiplied by 0.04626, our average plot size in acres, to obtain n, the "sample size." With the predicted values for P_{25} and P_{95} and the estimate for α from equation (16), the estimate for χ is

$$\hat{\chi} = 2.777427 / [\ln\{P_{95} - \hat{\alpha}\} - \ln\{P_{25} - \hat{\alpha}\}] \tag{17}$$

To obtain the estimate for the scale parameter, β, the equation for the second moment of the Weibull distribution is solved to give

$$\hat{\beta} = -(\hat{\alpha}\Gamma_1/\Gamma_2) + \sqrt{(\hat{\alpha}^2/\Gamma_2^2)(\Gamma_1^2 - \Gamma_2) + D^2/\Gamma_2} \tag{18}$$

where Γ_k is now based on the estimate for χ from equation (17) and **D** is the quadratic mean diameter obtained from the predicted trees per acre and basal area.

Based on the Kolmogorov-Smirnov goodness of fit test, only 35 out of 1291 predicted distributions were significantly different from the observed distributions at the 5% probability level. The system is consistent in that the quadratic mean diameter of the predicted diameter distribution will be the same as that obtained from predicted trees per acre and basal area (equations 4 and 6).

The models can be used to predict future stand structure for fertilized and unfertilized plantations when current diameter distribution, age, and soil group are known. As an example, suppose a 13-year-old plantation is growing on land in soil group **A** and predicted diameter distributions are wanted for ages 16, 21 and 23. The fertilization planned is 100 lbs/ac of P and 400 lbs/ac of N. From an inventory, the minimum diameter is known to be 2.0 inches (0.04 ac plot) and the 25^{th}, 50^{th}, and 95^{th} percentiles are 2.5, 3.0, and 3.8 inches. The stand has 600 trees/ac and 30 sq ft/ac of basal area, which give a quadratic mean dbh of 3.03 in. Using equations 16-18, the estimated Weibull parameters are determined to be 1.47, 1.69 and 3.40 for α, β and χ, respectively. With the system of equations presented above, the trees/ac, basal area, mean dbh and Weibull parameters are predicted for the desired ages (Tables 4 and 5).

TABLE 4. Trees/ac, basal areas and mean diameters for an example plantation.

		Basal area (sq ft/ac)		Mean dbh (in)	
Age	Trees/ac	Unfert.	Fert.	Unfert.	Fert.
13	600	30	30	3.0	3.0
16	596	39	56	3.5	4.2
21	586	51	108	4.0	5.8
23	579	55	129	4.2	6.4

The trees/ac (Table 4), estimated Weibull parameters (Table 5), and equation 9 together provide the necessary means to calculate diameter distributions for fertilized and unfertilized plantations (Figure 1).

TABLE 5. Weibull parameter estimates for an example plantation.

	Unfertilized			Fertilized		
Age	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\chi}$	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\chi}$
13	1.47	1.69	3.40	1.47	1.69	3.40
16	1.53	2.09	3.44	1.54	2.83	3.48
21	1.52	2.68	3.41	1.54	4.57	3.46
23	1.51	2.88	3.40	1.52	5.21	3.44

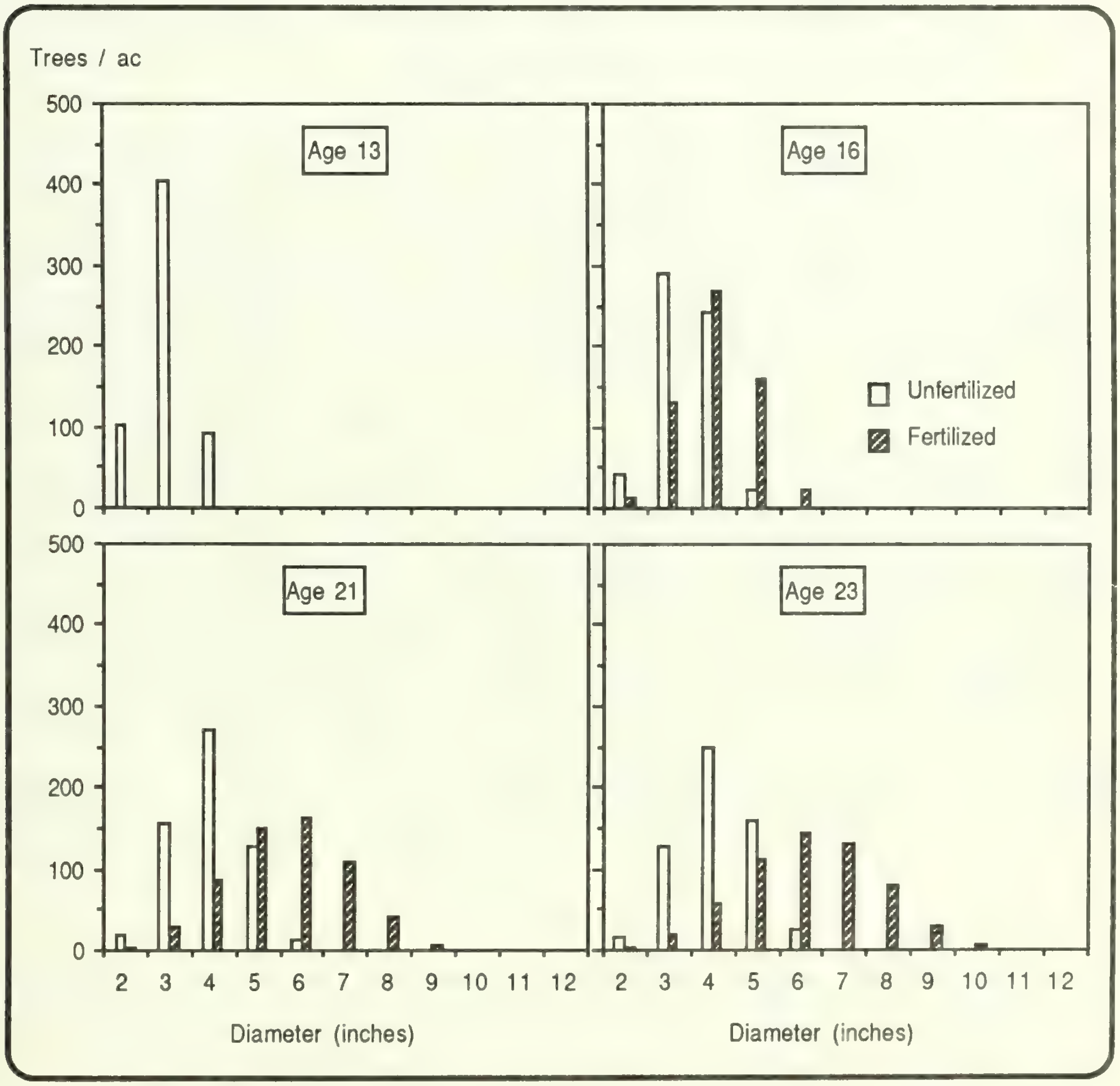

FIGURE 1. Diameter distributions for an example plantation.

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MODELING THE GROWTH AND YIELD EFFECTS OF FOREST FERTILIZATION ON RADIATA PINE PLANTATIONS IN NEW ZEALAND

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ABSTRACT. For fertilized radiata pine stands in Golden Downs Forest, basal area response was modeled as a nonlinear function comprising 3 submodels -- one each for fertilizer rate, time elapsed since fertilization, and stand conditions at the time of fertilization. The volume change resulting from the fertilizer-induced change in tree shape was modeled using a flexible polynomial taper equation within a distribution-based stand volume system. Accuracy and precision of estimates obtained from the altered growth model were comparable to those from an existing model. Estimates of stand volume were within approximately 17% of true volumes.

INTRODUCTION

Because fertilization has become a viable option in some cases, the incorporation of its effect(s) into forest growth models is needed to aid in developing optimal silvicultural regimes. In many early efforts, fertilizer effect(s) were modeled as an increase in site index. However, lack of a height response to, for example, nitrogen fertilization has been reported (Jacks et al., 1972) making this approach inappropriate. Another approach was more recently examined by Bruce (1981) who modeled basal area response to nitrogen as being dependent on site index and elapsed time since application. More work is needed to develop and refine this and other approaches.

A similar subject of importance here is the estimation of tree and stand volume after fertilization. A number of researchers have reported that fertilization causes a change in tree shape. Consequently, volumes of fertilized trees and stands may be misestimated by volume systems insensitive to form changes. Meng (1981) is one of the few who has developed a volume system to accommodate fertilizer response. He used a volume equation based on dbh and a series of dummy variables each representing 1 of 4 fertilizer treatments. This method provides only for discrete treatments, however, and not a continuum.

The purpose of this paper is to report results obtained from methodology developed to incorporate the effect(s) of forest fertilization into an existing growth and yield model.

DATA

The study area was Golden Downs Forest (Nelson Region, New Zealand), a publicly owned forest of approximately 30 000 ha managed for timber pro-

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duction by the New Zealand Forest Service. All data were collected from radiata pine (Pinus radiata D. Don) stands in Golden Downs where fertilizer trials began to be established in 1968. Each of the 4 trials used here was a replicated block design with treatments (including control) randomly assigned to each plot. On the 42 plots comprising the 4 trials, the following treatments were established: no fertilizer (control), nitrogen (N) only to 300 kg per ha), or a combination of N and phosphorous (P) to 216 kg per ha N and 240 kg per ha P). Buffer strips were established around each plot and, within the inner measurement plots, dbh of all trees and heights of a subsample of trees were measured at trial establishment and each year thereafter for 4 years. Each observation consisted of measurements of stand age, basal area, top height, and stocking at the beginning of the trial, and at a subsequent measurement period. At fertilization, stand age ranged from 6 to 15.6 years, basal area from 2.5 to 23.4 m per ha, and stocking from 190 to 1481 stems per ha.

In 3 of the trials, up to 3 trees were randomly selected from each plot and sectionally measured (Whyte 1971) at trial establishment and also 4 years later. In the remaining trial, selected trees were not measured at establishment. Section volumes were derived assuming each tree section to be a frustum of a cone, and all section volumes for a tree were summed to estimate volume. Regression analysis was then used to fit tree volume-basal area equations for each plot at each measurement period. By using these lines with per ha basal area values, relatively precise estimates of stand volume at establishment and 4 years later were obtained. These are here considered true stand volumes.

In addition, from the annual measurements of each plot, diameter distribution data -- minimum diameter, arithmetic mean diameter, and variance -- were extracted.

METHODOLOGY

To model fertilizer effects, 2 components were required: a forest growth function, and a stand volume system capable of accounting for the fertilizer-induced change in tree shape. The accuracy and precision of each part of these was assessed by predicting the quantity of interest and calculating the residual (actual - estimated) for each observation. Residuals were then summarized by calculating the mean, standard error, and prediction interval (Reynolds 1984) for a set of residuals. Using the t statistic, the mean bias (residual) was also tested to assess significant difference from zero.

FOREST GROWTH

An existing stand-level model for radiata pine in Golden Downs (Garcia, 1984) which uses a series of related differential equations was selected for modification. The model uses a "state-space" approach wherein the state of a forest stand is defined by the basal area, top height, and stocking at a particular age. The path along which each of the state variables moves through time is determined by the present state and site index of the stand.

Analysis indicated that only basal area was affected by fertilization. To obtain an estimate of basal area response for each treatment, Analysis of Variance was used to analyze basal area at each annual measurement period within each trial with basal area at the beginning of the trial used as a covariate. Basal area response for each treatment was obtained by differencing the mean basal area on control plots and fertilized plots.

Basal area response was found to be related to the time since fertilizer application, the amount of fertilizer applied, and stand characteristics at the time of application. Therefore basal area response was modelled using 3 distinct sub-models: 1)time, 2)rates, and 3)stand characteristics. The time and rates sub-models were fitted separately and used to estimate the stand characteristics sub-model to produce the full model. The estimated response for each of the 4 years following fertilization was then added to the basal area growth estimated by the unaltered model for the corresponding years. Following this period, the original model was used to advance the stand through time.

Graphs of basal area response suggested that 1)response peaked 2 years after application and decreased to zero after 4 years, and 2)response increased steadily with both N alone and N and P for the rates present in the data set. (Data limitations made it impossible to test for a response to P alone.) A number of non-linear models constrained through the origin were fitted for each quantity using a pseudo-Gauss-Newton algorithm. The time and rates sub-models which explained the most variance in basal area response were:

$$\underline{Tg} = \underline{t}^{1.556} \, \underline{e}^{(-0.404 * \underline{t})} \qquad (1)$$

$$\underline{R}^2 = 0.155 \qquad SE = 1.19 \text{ m}^2 \text{ per ha}$$

$$\underline{Fg} = \underline{N}^{-0.320} \, \underline{e}^{(\underline{N}/114.78)} \, \underline{e}^{(\underline{P}/372.95)} \qquad (2)$$

$$\underline{R}^2 = 0.285 \qquad SE = 1.10 \text{ m}^2 \text{ per ha}$$

where Tg is basal area response due to time (m^2 per ha), t is time since fertilization (years), e is the base of natural logarithms, Fg is basal area response due to fertilizer (m per ha), N is the amount of nitrogen applied (kg per ha), and P is the amount of phosphorous applied (kg per ha). Due to the non-linear fitting procedure, R^2 is the percent reduction in total sums of squares, and SE is the square root of the mean square error.

To fit the final sub-model and the full model, for each observation in the basal area response data set equations (1) and (2) were solved for Tg and Fg, respectively. The observed basal area response was then divided by the product of Tg and Fg to produce a transformed independent variable. Intercept-free stepwise linear regression was then used to produce both the stand sub-model and full model. Variables which described the stand at the time of fertilization -- basal area, top height, age, site index, and stocking -- and their logarithmic and inverse transformations were made available to the stepwise procedure which then incorporated the significant predictors into the model. To help overcome serial correla-

tion, a relatively stringent 0.005 significance level was adopted for variable inclusion. The resulting full model was:

$$\underline{Gr} = \underline{Tg} * \underline{Fg} * (17.625/\underline{Af} + 0.0914*\underline{Gf} - 0.070*\underline{S}) \qquad (3)$$
$$\underline{R}^2 = 0.862 \qquad SE = 0.35$$

where $\underline{Tg}$ and $\underline{Fg}$ result from equations (1) and (2), $\underline{Af}$ is stand age at fertilization (years), $\underline{Gf}$ is basal area (m^2 per ha) at fertilization, and $\underline{S}$ is site index (top height in m at age 20).

The signs of coefficients in the stand sub-model suggest that 1)younger stands respond more to fertilizer than older stands, 2)response increases with increased basal area at the time of fertilization, and 3)response decreases with increasing site quality.

The 3 sub-models may be considered nearly independent by virtue of describing different aspects of fertilizer response and being fitted almost completely separately, the contribution to $\underline{R}^2$ of each submodel may be partitioned. The time, rates, and stand sub-models explain 16%, 28%, and 42%, respectively, of the variation in basal area response suggesting that the most critical factor in achieving maximum response is the condition of the stand at the time of fertilization. In particular, the age of fertilization is most critical as this coefficient produced the highest $\underline{t}$ value by far of the stand characteristic variables in the stand sub-model.

FOREST VOLUME

Lowell (1986) presented methodology to produce a polynomial taper equation capable of providing unbiased and precise estimates of shapes and volumes of fertilized and unfertilized radiata pine trees in Pigeon Valley -- an area 30 km from Golden Downs. This was adopted here to produce the following taper equation:

$$(\underline{d}/\underline{D})^2 = 0.028\underline{hX} - 0.013\underline{DX} + 2.00\underline{X}^2 - 0.785\ln(\underline{h})\underline{X}^3 + 0.338\ln(\underline{D})\underline{X}^5 \qquad (4)$$
$$\underline{R}^2 = 0.987 \qquad S.E. = 0.074$$

where $\underline{d}$ is diameter (cm) underbark at height $\underline{l}$, $\underline{D}$ is diameter (cm) breast height overbark, $\underline{l}$ is distance (m) from tree tip, $\underline{h}$ is total tree height (m), and $\underline{X}$ is relative distance from tree tip ($\underline{l}/\underline{h}$).

Though equation (4) does not include any variable which explicitly quantifies fertilizer effect, Lowell (1986) concluded that the flexibility of the equation allows fertilizer effect to be quantified by implicit information contained in the variables $\underline{D}$ and $\underline{h}$.

Because a large exponent on $\underline{X}$ indicates that a particular term exerts a great predictive influence towards a tree base, the fifth term of the equation indicates that as $\underline{D}$ increases -- due to age and/or fertilization -- the stump becomes more pronounced, but this occurs at a decreasing rate as indicated by the logarithmic transformation. The area above the stump, however, decreases (relatively) at a decreasing rate as the tree increases in height also accentuating the relative increase in stump diameter.

To incorporate the taper equation into a stand volume system, predictive methodology for diameter distribution parameters and tree heights was necessary. The minimum, mean, and variance of a diameter distribution can be used with the Weibull function to generate a diameter distribution. This methodology was used to generate a diameter distribution by 1 cm classes. The tree height equation was then used to estimate the height of the mean tree in each class, the taper equation was integrated for volume for the tree of mean diameter and height in each class, this volume was multiplied by the number of trees in each class, and the volume of each class summed over all classes to obtain an estimate of stand volume. The equations developed to estimate the diameter distribution parameters were:

$$\underline{Dmin} = 93.51\sqrt{\underline{G}/\underline{N}} - 0.003111\underline{N} \qquad (5)$$
$$\underline{R}^2 = 0.993 \qquad SE = 1.6 \text{ cm}$$

$$\underline{Dmean} = 112.44\sqrt{\underline{G}/\underline{N}} \qquad (6)$$
$$\underline{R}^2 = 0.999 \qquad SE = 0.8 \text{ cm}$$

$$\underline{Dvar} = (\underline{G}/(pi/40000) - (\underline{Dmean}*\underline{N})/\underline{N})/(\underline{N} - 1) \qquad (7)$$
$$\underline{R}^2 = 0.473 \qquad SE = 4.7 \text{ cm}$$

where Dmin, Dmean, and Dvar are minimum, mean, and variance of a diameter distribution in cm, cm, and cm , respectively, A is stand age (years), G is basal area of a stand (m^2 per ha), and N is stocking (stems per ha).

Because the quadratic mean diameter has a constant of ($\sqrt{40000/pi}$) = 112.84 by definition, and Dmean is the arithmetic mean, variance may be recovered as shown in equation (7). Consequently, R^2 and SE for variance were not estimated through regression analysis but were obtained by examining residuals independently.

Though tree height is often estimated as a function of dbh, such an approach is inappropriate here due to the basal area response to fertilizer, but lack of a height response. Using heights of sectionally measured trees, the following equation was developed:

$$(\underline{h}/\underline{H}) = 0.857 + 0.245*\ln(\underline{RelD} + 1) \qquad (8)$$
$$\underline{R}^2 = 0.35 \qquad SE = 0.090$$

where h is tree height (m), H is stand top height (m), and RelD is the estimated percent of trees in the diameter distribution having a smaller diameter than a particular tree. RelD was estimated by using the quantities obtained from equations (5), (6), and (7) with a Weibull function to generate an estimated distribution.

RESULTS AND DISCUSSION

Estimates of both top height and basal area growth for each of the 4 years following fertilization were unbiased (Table 1) suggesting that the modified model produces accurate estimates of these quantities. Moreover, standard errors and prediction intervals for both quantities in fertilized stands are comparable to those for estimates for unfertilized stands indicating that the modified model produces top height and basal

area estimates for fertilized stands nearly as precise as those for unfertilized stands. This also suggests that within the range of data used, it was necessary to modify only the basal area growth component of the model, and by doing so the original model will produce estimates which are equally accurate and precise for each quantity.

Table 1. Reliability of growth estimates from the adjusted model.

Years Since Estab.	Unfertilized Mean Resid.	Unfertilized Std. Err.	Unfertilized Pred. Int.	Unfertilized n	Fertilized Mean Resid.	Fertilized Std. Err.	Fertilized Pred. Int.	Fertilized n
				Top height (m)				
1	0.00	0.10	0.95	18	0.05	0.06	0.90	48
2	0.19	0.14	1.14	12	-0.06	0.10	1.18	30
3	-0.13	0.19	1.80	17	-0.02	0.10	1.34	45
4	0.19	0.23	1.95	14	0.17	0.12	1.37	36
				Basal area (m^2 per ha)				
1	0.29*	0.12	1.10	18	0.11	0.08	1.11	48
2	0.28	0.23	1.87	12	0.07	0.19	2.14	30
3	0.47	0.23	2.09	17	-0.06	0.18	2.42	45
4	0.37	0.31	2.67	14	0.11	0.23	2.92	36
				Stocking (stems per ha)				
1	3.8**	1.1	10.4	18	2.0**	0.6	8.5	48
2	10.0**	3.5	28.9	12	4.6**	1.6	17.9	30
3	12.3**	4.3	40.0	17	6.9**	1.6	22.4	45
4	19.7**	7.3	63.1	14	10.8**	2.7	34.3	36

In Tables 1 and 2: * - significantly different from zero (95%)
** - significantly different from zero (99%)

Stocking tends to be underestimated for both types of stands, and estimates are relatively imprecise. Stocking and/or mortality are difficult parameters to estimate due to their semi-random nature. This problem is further compounded by the use of relatively small plots (0.09 ha or less) where the death of a single stem represents a large amount of mortality and may not accurately represent what is occurring throughout a stand. More data are necessary to determine whether or not the modified model adequately estimates stocking over time.

In the volume system, excepting mean diameter and variance, all quantities are estimated without bias (Table 2). The significant statistical bias in mean diameter is probably not of great practical significance, however -- precision is high and bias is only 1 mm. Further, stand volume estimates are not biased. The bias present in variance estimates undoubtedly causes the precision of stand volume estimates to suffer. Based on the prediction interval -- the 95% interval centered on the mean bias of the expected residual -- and the mean volume of unfertilized and fertilized stands (70.0 and 171.0 cubic m, respectively), stand volumes are estimated within 23% and 11%, respectively.

Estimates for fertilized stands appear much less precise than estimates for fertilized stands. However, because fertilizer caused a response, and because all plots at the start of the trial were classified as unfertilized, fertilized stands were composed of larger trees. With biologic entities, precision deteriorates as size increases. In reality, the

Table 2. Reliability of estimates the stand volume system and components within.

Unfertilized				Fertilized			
Mean Resid.	Std. Err.	Pred. Int.	n	Mean Resid.	Std. Err.	Pred. Int.	n
Tree Volume (Equation 4 - values are m)							
-0.0032	0.0023	0.0572	156	-0.0041	0.0036	0.1000	201
Minimum Diameter (Equation 5 - values are m)							
0.02	0.15	3.09	110	0.10	0.12	3.11	168
Mean Diameter (Equation 6 - values are cm)							
-0.10**	0.01	0.26	110	0.03	0.08	1.93	168
Variance (Equation 7 - values are cm^2)							
3.96**	0.45	9.33	110	4.32**	0.36	9.26	168
Tree Height (Equation 8 - values are m)							
-0.04	0.09	2.30	156	0.12	0.11	3.04	201
Stand Volume (Equations 4 through 8 - values are m^3)							
-0.5	1.3	16.2	39	0.3	1.6	19.3	39

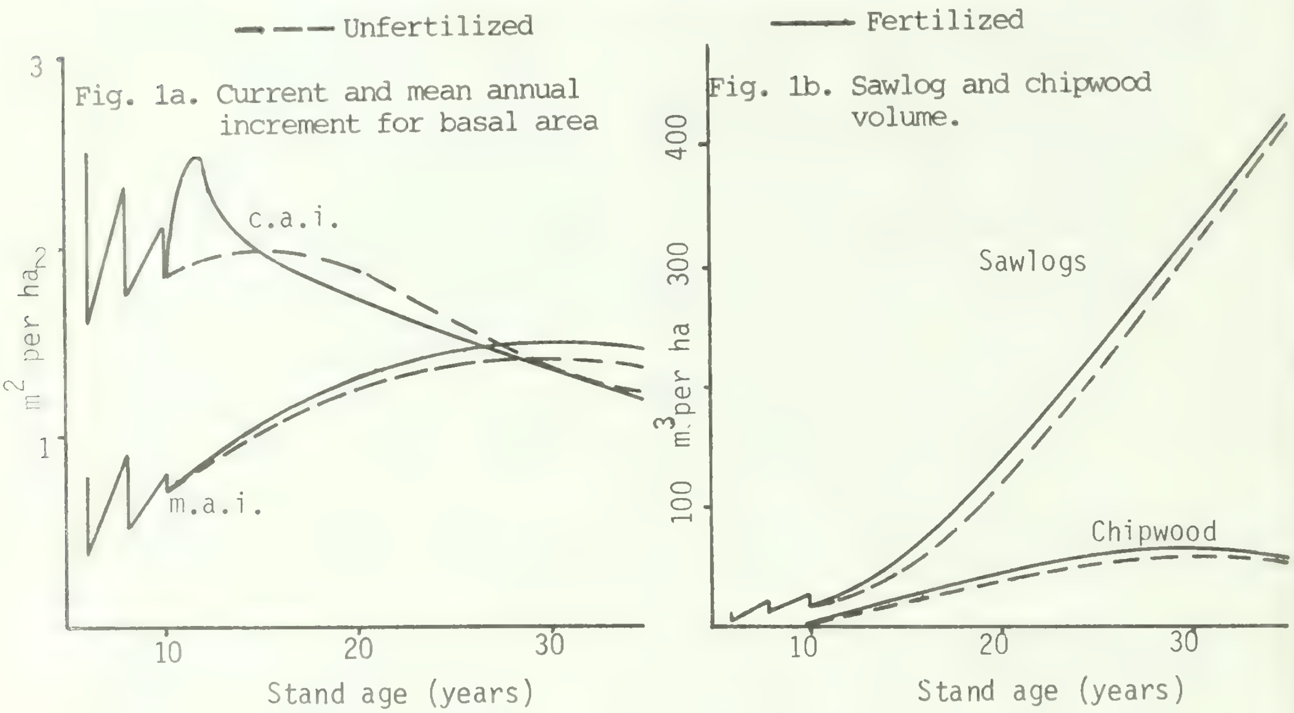
relative precision of estimates for fertilized stands was often better than for unfertilized stands as is the case for stand volume.

To demonstrate the use of the model, a silvicultural regime designed to produce maximum sawlog volume at a rotation age of 25 years was simulated. The stand was established at age 6 with 1000 stems per ha and 5.0 m per ha with a site index of 26. The stand was thinned twice and "grown" to age 35. The simulation was run twice -- in one case the stand was not fertilized, and in the other the stand received 200 kg per ha N and 100 kg per ha P. Figure 1 demonstrates that fertilizer affects both growth and volume. Fertilization affects the current annual increment for basal area in the 4 years following application causing the mean annual increment to be affected over the life of the stand. For volume, fertilizer increases the sawlog volume (25 cm top diameter) most, with minimal effect on chipwood (25 cm to 15 cm top diameter).

CONCLUSIONS

To model fertilizer effects, both growth and volume need to be considered. To model growth in this study, a basal area response model consisting of 3 sub-models -- time, rates, and stand -- was used to modify an existing growth model. Estimates from the modified model were nearly equally accurate and precise for both fertilized and unfertilized stands. Volume was estimated using a taper-based distributional stand volume system which also quantified the volumes of fertilized and unfertilized stands with equal accuracy and precision. Because fertilizer may not cause a height response, modeling its effect as a change in site quality may be inappropriate. Similarly, because fertilizer causes a change in tree shape, conventional volume systems insensitive to form changes will not adequately quantify volumes of fertilized trees and stands.

Figure 1. Development of unfertilized and fertilized stands over time.



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EVALUATION OF LONG-TERM FERTILIZER RESPONSE

Daniel Opalach and Linda Heath[1]

ABSTRACT. This paper describes a method that can be used to evaluate long-term fertilizer response. Emphasis is placed on how response behaves over time and the partitioning of response into direct and indirect effects. Remeasurement data from 34 research installations established in thinned second-growth Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) stands are analyzed and results presented to supplement the discussion. Results for these data indicate that stands fertilized with 224 kg nitrogen/ha continue to grow faster (14%) than control stands 12 years after fertilization. At this time, the increase in growth is mostly due to altered stocking brought on by the fertilizer in previous growing seasons (indirect effect). Very little of the response 12 years after fertilization is due to the improved nutritional status of these stands (direct effect). Long-term fertilizer response results presented in this fashion will aid in the development of fertilizer response equations for yield simulators.

INTRODUCTION

Nutrient amendments enhance the growth of many forest types. The additional growth due to fertilization is often presented as an increase in periodic annual increment (PAI) averaged over the length of the experiment. While this information is useful for evaluating the economic gain from fertilization, it provides little insight into how response is composed of direct and indirect effects or how response behaves over time. These issues are of concern to modelers attempting to incorporate fertilizer effects into yield simulators.

Partitioning fertilizer response into direct and indirect effects has been discussed by Comerford et al. (1980), Miller and Tarrant (1983), and Auchmoody (1985). The direct effect is that part of the response due to improved nutrition; the indirect effect is the remaining portion of the response due to altered stocking brought on by fertilizer in previous growing seasons. This concept applies well to nitrogen (N) fertilization of Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) stands and may also apply to other species and nutrient amendments.

Long-term N fertilizer response in Douglas-fir has been the subject of many recent publications. Interestingly, some have dealt entirely with direct effects (Peterson et al., 1986), others report responses that measure the combined effect of direct and indirect components (Barclay and Brix, 1985), and at least one discusses both (Miller and Tarrant,

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1983). In general, the statistical analyses are not straightforward and require simplifying assumptions.

The objective of this paper is to describe a method that can be used to evaluate long-term response to a single application of fertilizer. The method is well suited for analyzing remeasurement data collected from several research installations located in the same forest type. Emphasis is placed on determining the response pattern and partitioning response into direct and indirect effects. Methods appropriate for the analysis of fertilizer effects for a single research installation are discussed by Lipas (1979), Barclay and Brix (1985), and Mize and Schultz (1985).

MATERIALS AND METHODS

DATA DESCRIPTION

The method discussed in this paper is illustrated using data from the Regional Forest Nutrition Research Project (RFNRP), a cooperative forest fertilization research program administered by the University of Washington. For information about the objectives and analytical methods of the RFNRP, see Hazard and Peterson (1984).

The data come from 34 RFNRP research installations in thinned second-growth Douglas-fir stands. Each installation contained six 0.04-ha or larger plots that were thinned to 60% of their original basal area. Two plots were controls, two plots were fertilized with urea (46% N) at 224 kg N/ha (200 lbs N/acre), and two plots were fertilized with urea at 448 kg N/ha (400 lbs N/acre). Treatments were randomly assigned and fertilizer was broadcast uniformly by hand within plot boundaries and surrounding buffer zones. Eight years after installation establishment, one replicate of each treatment was refertilized with 224 kg N/ha.

Tree measurement data were taken at the time of installation establishment and every two years thereafter. For each plot, initial diameter at breast height (DBH) measurements were taken for all trees greater than 3.94 cm (1.55 inches) in DBH. The heights of ten dominant and codominant trees were also measured to estimate site index (King, 1966), and to estimate volume using tarifs (Turnbull et al., 1972).

Mean initial stand conditions (post-thinning) for these installations are:

breast height age	30 years	
site index	34.7 m	114 ft
density	840 trees/ha	340 trees/acre
basal area	27.6 m^2/ha	120 ft^2/acre
total cubic volume	262 m^3/ha	3750 ft^3/acre.

LONG-TERM GROWTH RESPONSE ANALYSIS

Response to fertilizer is defined as

$$R = \begin{array}{c}\text{mean}\\ \text{growth rate of}\\ \text{fertilized stands}\end{array} - \begin{array}{c}\text{mean}\\ \text{growth rate of}\\ \text{control stands.}\end{array} \qquad (1)$$

R measures the combined effect of direct and indirect components. Note that R changes over time. In general, R attains a maximum shortly after fertilization and decreases thereafter. Long-term response can be studied by examining R and its direct effect component for several growth periods following treatment.

Analysis of covariance is used to estimate response and direct effect for each growth period. Two separate analyses are required for each period (except the first): one to determine response and one to determine direct effect. The general model for volume PAI or basal area PAI is

$$Y_{ijk} = u + T_i + B_j + \beta(S_{ijk} - S_{...}) + e_{ijk} \qquad (2)$$

where Y_{ijk} = PAI of replicate k, installation j, treatment i
u = mean PAI
T_i = main effect of treatment i
B_j = block effect of installation j
β = regression coefficient
S_{ijk} = initial stocking or current stocking covariate
$S_{...}$ = mean stocking
e_{ijk} = error.

All effects are fixed. Errors are assumed to have a normal distribution with mean 0 and unknown but constant variance. Since main effects are of primary interest, homogeneity of regressions is assumed and interaction effects are not included in the model. The model can be augmented with higher order $(S_{ijk} - S_{...})$ variables if the relationship between Y_{ijk} and $(S_{ijk} - S_{...})$ is nonlinear. Homogeneity of regressions is assumed for these terms as well.

Stocking refers to volume per unit area or basal area per unit area. Initial stocking is stocking at the time of fertilization and current stocking is stocking at the beginning of the growth period. In the first growth period, response equals direct effect because initial stocking and current stocking are identical.

The covariate S_{ijk} plays an important role in the estimation of treatment effects. If the covariate is initial stocking, then T_i is the response (R in equation (1)) to treatment i. This covariate is used to adjust treatment effects for differences in initial stocking that existed at the time of fertilization. If the covariate is current stocking, then T_i is the direct effect of treatment i. In addition to adjusting for initial stocking differences, this covariate adjusts treatment effects for differences in current stocking brought on by fertilizer in previous growing seasons. This interpretation is a consequence of the assumption of homogeneous regressions.

AN EXAMPLE

For the purpose of illustrating the long-term analysis method, gross volume PAI is used as the dependent variable, but other dependent variables (e.g., basal area PAI) could be used. Volume is measured in cubic meters and includes top and stump.

The data were collected over six two-year periods so 11 analyses of covariance were required to estimate the responses and the direct effects for each of these periods. It should be noted that these estimates contain an unknown bias due to correlations in the data. Although treatment effects were estimated for all fertilizer levels, only results for the 224 kg N/ha treatment are reported here.

Estimates of responses and direct effects for each growth period are plotted relative to mean control volume PAI to reveal the response pattern (Figure 1). All responses and direct effects are significant ($p < 0.10$) except direct effects eight, ten, and 12 years after fertilization. Direct effect makes up a large portion of the response in the first six years after treatment, but decreases thereafter. However, response is still considerable 12 years after fertilization (14%).

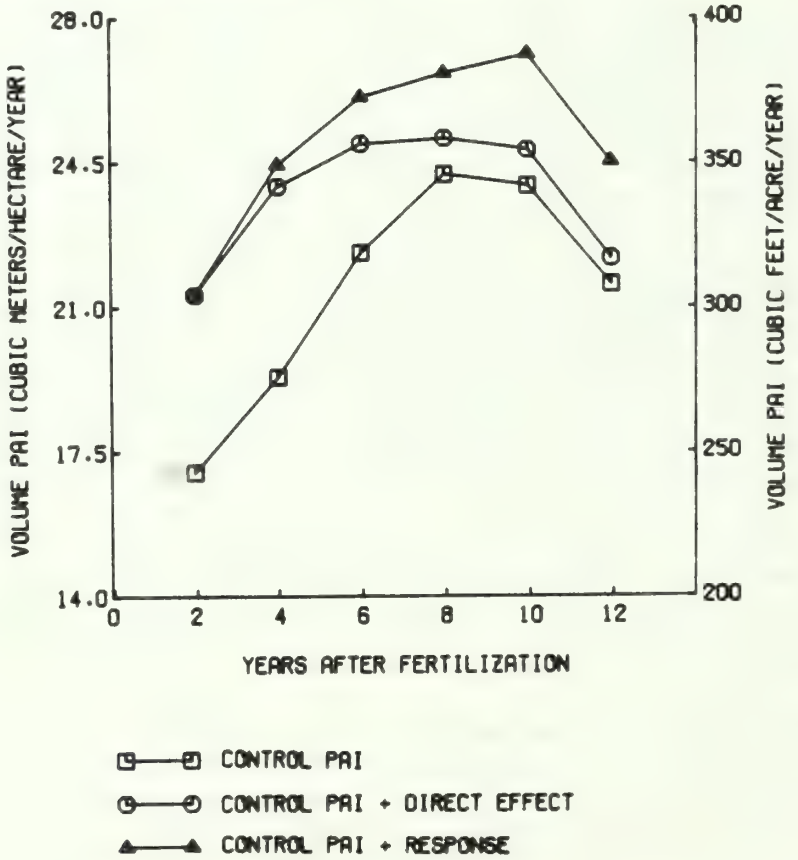

Figure 1. Response pattern for second-growth thinned Douglas-fir stands. Although the direct effect is no longer significant ($p > 0.10$) six years after fertilization, the response is still significant ($p < 0.01$) 12 years after fertilization.

DISCUSSION

REASONS FOR USING ANALYSIS OF COVARIANCE MODEL

The primary goal of the analysis is to estimate and test the significance of treatment effects by two-year growth period, and the model serves this purpose well. Changes in the experimental design due to the addition of treatments and loss of plots (due to accidental destruction) make it difficult to pool data from all growth periods for a combined analysis. Also, for RFNRP data, it remains to be shown that results from a combined analysis are superior to results from separate analyses.

POTENTIAL PROBLEMS AND LIMITATIONS OF THE MODEL

As stands age, initial stocking explains less and less of the variability in PAI. Thus, at some point in time it may not make much sense to use initial stocking as a covariate in the model. For RFNRP data, initial stocking variables remove a significant amount of variation in two-year PAI measurements observed ten years after fertilization.

Fertilization has a dramatic impact on current stocking. Soon after fertilization (approximately four years), stocking levels for fertilized and control plots are significantly different in the example above ($p < 0.10$). In cases where nothing is known about the relationship between the covariate and the dependent variable, researchers are advised not to use covariates that exhibit this problem: treatment effects may be confounded with different levels of the covariate. However, in Douglas-fir, it can be argued that N fertilization does not drastically change the fundamental relationship between growth and growing stock (the assumption of homogeneity of regressions). Therefore, if the direct effect is significant, it is attributed to improved nutrition.

ADDITIONAL ANALYSES

Response to fertilization might depend on location. Two approaches are typically used by the RFNRP to investigate this possibility. The approach chosen depends on the number of installations in the data.

For small data sets with few installations (30 or less), equation (2) can be augmented with interaction effects $(TB)_{ij}$. This approach becomes impractical for problems with more installations--the design matrix becomes too large to manipulate for many statistics programs. In those instances where interaction effects have been computed, results for basal area PAI models and volume PAI models are not consistent. Interaction effects are typically significant ($p < 0.10$) in basal area PAI models and not significant ($p > 0.10$) in volume PAI models.

A regression approach can be used to study the relationship between response and stand attributes such as age, site index, and stocking. In this approach, PAI is regressed on a set of stand attribute variables and treatment dummy variables. Treatment dummy x stand attribute variables (interactions) are introduced into the model and tested for significance. The presence of a significant interaction term in a PAI model indicates that response is related to the stand attribute in the term. Results from

analyses on thinned Douglas-fir stands indicate that basal area response is inversely related to stocking and site index. Volume response for these stands is not related to stocking or site index (RFNRP, 1982).

Hazard and Peterson (1984) proposed a model that features installation response (observed fertilized PAI minus observed control PAI) as the dependent variable rather than PAI. This choice of dependent variable makes it relatively easy to test the effects of stand attributes on response. However, the use of this dependent variable reduces the six degrees of freedom associated with each installation (one degree of freedom for each plot) to two degrees of freedom.

DURATION OF FERTILIZER EFFECT

Researchers often attempt to quantitatively determine the duration of fertilizer effect, that is, the length of time that fertilizer has an effect on stand growth. The RFNRP determines the duration of fertilizer effect by examining the sequence of direct effects and their standard errors. The duration of fertilizer effect is the number of years that direct effects are significantly greater than zero. Other definitions exist in the literature (e.g., Miller et al., (1976) and Barclay and Brix (1985)), and it is often difficult to compare results from different studies for this reason.

CONCLUSIONS

Nitrogen fertilization has two distinct effects on stand growth--a direct effect and an indirect effect. The direct effect represents the increase in growth due to improved nutrition. The indirect effect represents the increase (or decrease) in growth due to altered stocking. The sum of both effects is called response.

Long-term response can be evaluated by examining response and its direct effect component for several growth periods following fertilization. A method that uses analysis of covariance models was presented to estimate these quantities. These estimates can be plotted relative to control stand growth to reveal the response pattern. Results presented in this fashion may aid modelers formulating fertilizer response equations for yield simulators and might also be used to validate yield simulators that have been augmented with fertilizer response equations.

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IMPLICATIONS OF GENETIC IMPROVEMENT FOR THE GROWTH AND YIELD OF TREES AND STANDS

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ABSTRACT. Genetic improvement has begun to have a major impact on forest management in the United States and around the world. This discussion uses the basic genetic principles and standard practices of tree improvement to build a set of expectations about the expression of genetic gain in stand productive potential, and recommends an approach to quantification of gain on an ongoing basis into the future.

INTRODUCTION

For decades the quantification of forest growth and yield has been a major focus of study and operational practice in forestry. Central to this focus is a single question, key to planning of most aspects of the forest management enterprise:

"What is the value-production potential of a forest stand over time?"

Value-production potential is an outcome of the action and interaction of the many biological processes driving stand development. In turn, the rate and pattern by which these stand development processes operate through time are driven by the genetic potentials of the trees in the stand, by the site and cultural environment through which genetic potential is expressed, and by interactions of environmental factors with one another and with the genotypes in the stand.

Historically it has been possible to project the course of stand development on the basis of environmental effects alone, because natural stands and woodsrun (unimproved) plantations of a given species, in a given geography, consist of trees of diverse genetic potential distributed essentially at random both among and within stands. The average genetic potential does not differ in expected value from one stand to the next.

Large-scale tree improvement, however, has dramatically changed this picture in some parts of the world. The average genetic potential of any stand can now be controlled and may vary considerably and consistently from stand to stand. This scenario makes it unwise to ignore genetic effects on the rate and pattern of stand development and ultimate value production. Therefore, our key question becomes:

"What is the value-production potential of different genetic populations on a given site over time?"

particularly in terms of the genetic populations of greatest

interest today: that is, improved and unimproved populations, and different improved families. In recent years, data have begun to suggest that families in mixed-family progeny tests are fairly stable in rank through and past crown closure, and may also rank similarly in pure-block plantings (Gladstone et al., 1987). However, many questions have been expressed about the long-term stand performance of families selected for individual-tree superiority under essentially free-to-grow conditions, particularly if they are deployed in pure blocks (Ford, 1976; Franklin, 1979). Very little long-term stand data is available.

The evaluation of genetic effects on stand development and productive potential has been discussed by several authors (Burkhart and Matney, 1981; Switzer and Shelton, 1981; Nance et al., 1986; Sprinz, 1987). This paper will take a slightly different tack, using the basic biology and practice of genetic improvement to suggest some general expectations about the impact of genetic improvement on stand production. Experimental results will be discussed relative to these expectations. Finally, some specific suggestions will be made regarding quantification of genetic improvement effects in the future.

GENETIC IMPROVEMENT - FUNDAMENTALS AND PRACTICES

Trees as biological organisms exhibit variation at many levels, among species, among geographically separated groups (provenances) within a species, among stands within a geography, and within stands. Some of this variability is genetic - in other words, consistent differences exist which reflect differences in genetic makeup. At the species, provenance and stand level, genetically-distinct groups or 'genetic populations' differ in the frequency of gene combinations conferring a set of observable attributes.

The genetic improvement process changes observed value for specific attributes by increasing the frequency of 'desirable' gene combinations for those attributes in commercial stands. The activity may consist of selection and deployment of desirable species and provenances, as well as selection and breeding of genetically superior individuals and deployment of their offspring through multiple generations. The concept of an introduced change in the frequency of gene combinations is key to development of expectations about genetic improvement effects. Let us briefly review the 'basics'.

A 'gene' refers to a set of bases on one strand of a chromosome. In diploid organisms like trees, chromosomes consist of paired strands of DNA, so genes are carried in pairs. The 'spot' on a chromosome where a single gene pair is located is called a 'gene locus' (plural 'loci'). Genes at a given gene locus can take many different forms, or 'alleles'. In the case of a simply inherited attribute, Gregor Mendel's smooth and wrinkled peas, only two alleles exist, and different paired combinations of those alleles produce different morphologies. Most commercially

important attributes of forest trees, like yield, stem form or response to climate and pests, are thought to be inherited in a far more complex manner, through many, perhaps hundreds, of gene loci and many different alleles at each locus. The 'genetic potential' of an individual for a specified attribute reflects small incremental impacts of individual alleles, of combinations of alleles, and of combinations of loci. Huge numbers of possible genetic combinations exist, along a continuum of 'desirability'. Add to this genetic complexity the fact that genetic potential (genotype) is only one component of observed value (phenotype) for an attribute; environmental effects and interactions of genetic and environmental effects also contribute to observed value.

So how do genetic improvement practices modify the frequency of desirable gene combinations, and what do we expect to be the observable results? Let us focus entirely on genetic improvement within species and provenance.

Genetic improvement influences the genetic composition of stands by restricting reproduction only to those trees having a high probability of carrying desirable genotypes. We speak of 'probabilities' here because we cannot directly measure the genetic potential of a tree free of the confounding effects of its environment. If a set of trees is selected on the basis of observed phenotype alone, the likelihood is high - for yield attributes in particular - that their phenotypic superiority results from environmental effects. We expect only a small change in genetic potential by using those trees as parents. However, we can increase the probability that an outstanding phenotype is truly an outstanding genotype. The smaller the 'elite' proportion of the population that is selected - the greater the 'selection intensity' - the more likely it is that the selections are genetically superior, as long as no obvious environmental biases are present. Also, indirect information about an individual's genotype can be derived from the individual's relatives. Groups of offspring (progeny) or siblings of an individual are more likely than unrelated groups to carry gene combinations identical to those carried by that individual. When the progeny or sibling groups are replicated across a variety of environments, the average performance of those groups across environments reflects their average genetic potential. If an individual's relatives show outstanding average genetic potential, this increases the likelihood that the individual itself is outstanding genetically.

Hence the existence of 'progeny tests' consisting of groups of offspring from selected parents (families), replicated both within and across environments chosen to represent a range of 'operational' sites. The offspring groups provide information on the genetic quality of their parents, allowing only the genetically superior parents to be left to reproduce in seed orchards. Different offspring from a single parent - a family of siblings - provide genetic information about one another so that

the best of them can be selected to comprise another generation of parents. The ability to detect differences among offspring groups accurately and precisely is essential to the selection of genetically superior parents, and therefore, to the magnitude of genetic gain which can be expected. For this reason, progeny tests most often are planted in small plot field designs with an emphasis on replication and careful environmental layout.

At the outset the selection of superior individuals is typically practiced in unimproved natural stands or plantations, where the location of an individual's siblings or offspring is unknown. Selection at this stage is therefore on the individual's phenotype alone, although a strong emphasis is placed on comparing each individual with neighbors on similar microsites so that any observed superiority is more likely to be genetic. The criteria used for selection vary; generally the greatest emphasis is placed on stem Dbh and height, but quality and adaptability traits may also be considered. The selected trees are usually then grafted into seed production orchards, and managed aggressively so that within several years seed is produced which largely result from intercrossing among selected parents.

At the time of orchard establishment, a parallel effort is conducted to intercross the selected parents, and seed from those crosses are collected and planted into progeny tests. On the basis of regular assessments of Dbh, height and survival through the early years of stand development, offspring groups are compared, and parents whose offspring are less than outstanding for these attributes, or whose offspring are poor in quality or adaptability, are removed from the orchards in a step called 'roguing'. Early measurements are also used to select individuals from the progeny tests themselves, incorporating individual and sibling information, to generate a new production orchard. With this step, the process then begins again.

When selection is careful and rigorous, offspring of the selections are expected to carry 'desirable' gene combinations at greater frequency than the population from which their parents were selected. Given that the environment in which the offspring are grown is no poorer, we therefore expect an increase in the observed mean for the attributes under selection. The change in the observed mean from the parental population to the offspring population which can be attributed to genetics is 'genetic gain'.

The basic genetics of the system allow us to develop certain broad expectations about the magnitude of gain which can be expected.

1. The offspring of a particular selected parent will not perform as well, on average, as the parent itself in the same environment at the same age.

Why? First, we cannot select directly for high genetic potential. Even when relatives are used to provide genetic

information about a particular outstanding individual, the individual's genotype and environment are uniquely its own, and there is some likelihood that it is outstanding for environmental reasons only. Second, through the sexual reproduction process, gene combinations which made a set of parents genetically superior are broken up, and the genes recombined in new ways. The only effects which can be counted upon from one generation to the next are the average effects of the individual genes.

2. The magnitude of genetic gain will vary widely, between unrogued and rogued production orchards, among generations, and among organizations.

Orchard roguing can be viewed as a separate selection step, and the parents remaining after roguing are more outstanding on average than the unrogued orchard group. Offspring from a rogued orchard are likely to show more genetic gain than offspring from the unrogued orchard.

Also, selection in natural stands will often result in less genetic gain than selection from well designed progeny tests. First, heterogeneity of microsite and spacing in natural stands makes it difficult to compare even adjacent trees on a similar environmental basis. Second, the genetic structure of progeny tests makes it possible to select on individual and sibling information, increasing the likelihood that observed superiority is genetic in basis. In natural stands, selection must be on an individual's phenotype alone. If natural stand selection is practiced without a high selection intensity, and without care to evaluate candidates with a keen eye to environment, it is possible that this first-round selection step could result in little or no genetic gain.

Organizations will also show different gain results. Talbert (1982) reported estimates of genetic gain for age-8 average height which ranged from -.77 to +8.0 percent, from a sample of 33 orchards across the North Carolina State University-Industry Tree Improvement Cooperative. This variation may result from differences in selection practice (selection intensity and criteria), in progeny test layout, design and maintenance, and in the random sampling of genotypes available for selection.

3. Tree improvement as described above is not expected to make an appreciable change in observed variation among trees, even with deployment of family blocks.

First, we expect little reduction in the magnitude of genetic variation. Genetic potential results from the action of many genes and loci, each with small incremental effects, acting in complex combinations. The loss of a gene in the course of selection should not have much impact on the range of types present. Even a single family is highly genetically variable, since each offspring is the result of a new recombination of the genes carried by the parents. Second, most of the variation we

observe among trees for important yield traits is environmental rather than genetic, so small changes in genetic variability are likely to be hidden.

With these general guidelines in hand, it is possible to suggest some general expectations about genetic effects on stand production.

GENETIC GAIN IN PRODUCTIVE POTENTIAL

Given the wealth of effort already put into mathematical characterization of a small number of key fundamental processes of stand development, it would be very useful to evaluate differences in the rate and pattern of stand development among genetic populations in terms of the same key processes. These can be described in general terms as:

* Growth in stand volume over time
* Mortality (size-density) over time
* Development of stem size distributions over time
* Changes in relative stem dimensions over time

This discussion will focus on the first three.

STAND VOLUME GROWTH OVER TIME

1. Genetically improved stands will tend to exhibit more rapid height growth and volume production than unimproved stands prior to the onset of intense intertree competition, as long as site resources are sufficient to allow growth differences to be expressed.

Organizations which have made a commitment to aggressive tree improvement have, in general, used high selection and testing standards. Therefore, basic genetics and experience from breeding of other agronomic crops indicate that we can expect to observe an appreciable increase in genetic potential for average height and Dbh, and in some programs, for quality and adaptability characteristics, as a result of tree improvement. Therefore, as long as average environmental quality does not decline from one generation of improvement to the next, the observed (phenotypic) value for these attributes will tend to improve. It also follows, then, that as long as early survival does not differ between improved and unimproved stock (and on sites to which they are adapted, improved planting stock has been shown to survive at least as well, and often better, than unimproved planting stock), stand volume during the free-to-grow stage should be greater for improved stock.

Of course, there are caveats. As we mentioned before, gain will vary widely with time and among organizations. There are also indications that the magnitude of gain, and of differences among improved families, can vary considerably across sites, although the rankings of the improved families are usually similar across

sites (as long as the sites do not represent an environmental extreme) (Weyerhaeuser unpublished data: 6-8 year old loblolly pine plantations, 11 year old loblolly pine Edaphics trials, loblolly pine and Douglas-fir progeny tests). Also, this statement is meant to apply to pre-competitive stands, since selection in progeny tests tends to take place during this early phase.

What can we expect in terms of differences after intense intertree competition gets underway?

2. Annual volume growth and survival of loblolly pine trees through 20 years has been shown to relate strongly to their age-5 height position (Switzer and Shelton, 1981). If improved families are planted in mixtures, we would expect families with the best early height growth to show a long term volume production advantage, and volume differences between early fast and slow growing families would be expected to increase with time, assuming no differences in response to competition among families. If families are planted in blocks, families with an early advantage in height growth are not competing directly with slower growing families, so this effect cannot be applied.

3. It is not clear that a site index lift alone will adequately describe differences among families, and between improved and unimproved stock, over the long term.

The height growth of dominant trees on different sites reflect site quality attributes like soil moisture availability, nutrient status, and a large variety of other effects. These dominant-height growth patterns have been used to develop height-age curves for different sites. In contrast, differences in the dominant height growth of different genetic populations on the same site reflect differences in the genetic growth response of those populations to the same site attributes. Biologically it is difficult to see a priori why differences among sites for the same genetic population would manifest themselves in the same way through time as differences among genetic populations on the same site.

Empirical data present a mixed story. Buford and Burkhart (1985) found similar shapes but different levels of height-age trajectories for 15 and 16 year old loblolly pine progeny test families and 25 year old loblolly pine seed sources, supporting the view that a site index lift could adequately represent family differences in height-age trajectories. However, other analyses have shown family and source differences in the shape and level of height-age curves, with some families/sources growing more rapidly early on and the others beginning to catch up later (Sprinz et al., in press; Talbert et al., 1987; Schmidtling, 1984; Sprinz, 1987). Further data will be of great value.

Two areas of caution should be introduced relative to the site-index lift approach, however. First, progeny test height data

typically refers to average height, not dominant height. Average height differences overestimate dominant height differences. Second, most data on improved families will come from fairly young progeny tests, and site curves often are fit to predominantly older stand data. The ability of a given set of site curves to accurately project site index from early data will be a critical factor.

MORTALITY/SIZE-DENSITY OVER TIME

1. Improved stands on average should not respond less favorably to competition than unimproved stands at the same relative density.

Natural stand and progeny test selection candidates typically must exhibit outstanding performance under competitive conditions similar to their unselected neighbors before they will be chosen as final selections. Trees with missing or very small neighbors are usually eliminated. In addition, most programs favor fast-growing types with compact crowns and small or average-sized branches.

However, because of their more rapid early growth, improved stands are likely to arrive at a given relative density more rapidly than unimproved stands. Therefore, at some standard age improved stands may show more mortality than unimproved, simply because the improved trees average larger at that age.

2. Different improved families may show different growth or mortality rates for a given relative density.

In analyses of long-term loblolly pine studies by Buford (cited in Nance et al., 1986), Talbert et al. (1987) and Schmidtling (1987, in these proceedings), seed sources did not differ significantly in the slope of their asymptotic size-density relationships, but they did differ, sometimes substantially, in the level of those relationships. Loblolly pine families planted in a Nelder's wheel spacing study differed in individual-tree basal area growth for the same competitive stress (as indicated by Area Potentially Available, APA), but the family differences in competitive response could be explained by family differences in average basal area per tree (Nance et al., 1983). In a similar analysis of loblolly pine progeny test data, Nance and Land (1987) found that families differed significantly in basal area growth per unit of APA, but the average size of the families themselves was not a part of the analysis.

THE FUTURE - "THE CERTAINTY OF UNCERTAINTY"

Certain aspects of the future can be foreseen with some certainty and therefore can guide our approach to quantification of genetic improvement effects.

1. Genetic selection is likely to continue to emphasize

individual-tree attributes in young, mixed-family or small plot progeny test stands. First, for high selection intensity we must screen of many families, and it is very costly to do this in large family blocks with acceptable replication. Second, it would also be extremely costly to delay selection decisions until differential competitive responses became evident, and in mixed-family tests the importance of early height differences to long-term yield suggests that the rankings of families might not change much even if we were to wait.

2. It will be increasingly critical to capture quality differences in projections of stand value production for improved stands. Loblolly pine improvement programs have already made major improvements in stem straightness through rigorous selection, and wood property improvement is likely to become more and more common practice with time.

3. The genetic populations we are attempting to characterize will change very rapidly, because of orchard roguing, use of different groups of families, and turnover of generations. A long-term study planted today could well contain a sample of families which was unrepresentative of the families in use by the end of the study.

4. The magnitude of gain and the manner in which it is expressed will vary greatly among organizations due to differences in tree improvement practice, and it will be very difficult if not impossible to quantify those differences.

Given these trends, certain things will be mandatory. We should focus on genetic improvement impacts on key biological processes only, and recognize and accept uncertainty with respect to second-order effects and interactions. Also, even for the key biological processes, innovative, process-oriented experiments must substitute for giant, multifactor empirical trials, because the cost of a purely empirical approach for an ever-changing genetic population is too great to be borne by an industry increasingly faced by tight resources. We believe that it will be a vital step for family yield comparisons to become a standard part of forestry practice. Replicated groupings of woodsrun with the most used families or family mixtures, planted on key environment types, will not only provide ongoing estimates of genetic gain, but will allow us to verify the stand-level performance of families selected for individual-tree yield from mixed-family tests.

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SYMMETRICAL RESPONSE-SURFACE REGRESSION MODELS FOR AGE-AGE AUTOCORRELATION IN VOLUME GROWTH OF CRYPTOMERIA TREES

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ABSTRACT. The efficiency of early selection in a forest tree improvement program depends on how closely the juvenile expression is correlated with the mature character. Here, the juvenile-mature correlation is generalized into age-age autocorrelation by removing the condition that the juvenile age must be smaller than the mature age. The square correlation matrix which has a value 1.0 on the diagonal seems to fit a symmetrical response-surface model:

$$Z = B0 + B1(X + Y) + B2(X * X + Y * Y) + B3(X * Y)$$

During the exponential growing period the two ages should be transformed by the natural logarithm into X and Y; while at the linear growing period, square root transformation is appropriate. The dependant variable, Z, is the correlation in the additive error model and it should be the logarithmic transformation of the correlation in the multiplicative error model. Using volume growth of 51 cryptomeria trees from age 3 to 30 as an example, the symmetrical response surface models were highly significant with the degree of determination above .9. More than 60% of the total variation was accounted for by the crossproduct and 20% by the quadratic terms.

INTRODUCTION

Tree improvement is a long-term investment. In order to shorten the breeding cycles, we would prefer to make selection as early as possible. Another advantage of making an early selection is that trees can be planted closer and hence the land-use can be more economical (Kung 1973).

The efficacy of early selection is related to the correlation between the early assessment and the late assessment of the trait being improved (Kung 1975). Usually, early selection is less effective, but it may be more efficient than late selection in terms of genetic gain per unit of area and per unit of time (Kung 1973, Bohren 1975).

Lambeth (1980) found that juvenile-mature correlations in the literature were more predictable than may have been expected. His prediction equation was:

$$r = a + b \text{ LAR}$$

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where r = age-age correlation, a, b = repression coefficients, and LAR = logarithm of age ratio = log (youngest age/oldest age). Based on eight data sets he had examined, the value of coefficient "a" ranged from 1 to 1.02, and for "b", 0.29 to 0.35. The fit between data points and regression line in each case was generally good.

According to Lambeth's model, the juvenile-mature correlation is constant for a given age-ratio. However, in practice we found that it changed with ages except when the age ratio is a unity. For example, given an age-ratio of 1:2 but with varying early and late ages, the correlations in our study were found to be as follows:

age-ratio	3/6	4/8	5/10	6/12	7/14	8/16	9/18	10/20	15/30
r	.710	788	.822	.716	.665	.653	.639	620	.603

Clearly, such systematic trends need to be considered in alternated models. The objective of this paper therefore is to build a response-surface model for age-age autocorrelation without the condition of specifying a ratio of earliest age over the latest age.

MATERIALS

The cryptomeria data were collected by the Experimental Forest of National Taiwan University, Taiwan, China. Trees were planted between 1912 to 1938 with 3,000 to 4,300 stems per hectare. The size of the 14 permanent growth plots used in this study ranged from 0.11 to 0.15 hectare. Starting from 1927 to 1970 in approximately a 5-year interval, dbh was measured with a caliper for all trees within the plot. The approximate sample tree, based on the average diameter, was cut for the stem analysis. Total stem volume inside bark was calculated to 0.0001 cubic meter. The data base for this study was presented in Table 1.

METHODS

Forest geneticists have recently recognized that the development of a plantation falls into three periods. In the juvenile period, variances in environmental error increase logarithmically, because seedlings that are genetically superior in this phase of development rapidly capture their microsites and enter into a period of free growth. As the more slowly developing seedlings also capture their sites, the stand becomes more uniform in growth development during this maturing phase. Finally, the rapid developing phenotypes are slowing down while less rapidly developing phenotypes are catching up. During this codominance-suppression phase the environmental error again increases rapidly but genetic variance does not reappear (Namkoong et. al. 1972, Franklin 1979). Since the age-age correlations within a given phase are generally predictable while those across phases are unpredictable we therefore arbitrarily separate the data into two growing periods: the exponential phase is from age 3 to 9 years and the linear phase is from 14 to 30 years. The codominance-suppression phase will not be studied in this paper due to insufficient data.

TABLE 1. Volume yield of individual cryptomeria trees in Taiwan.

Age (Year)	Volume: Mean (Cubic Meter)	Volume: Standard Deviation (Cubic Meter)	Sample Size (No. of Tree)
3	0.00044	0.00088	51
4	.00185	.00260	51
5	.00536	.00593	51
6	.01168	.01042	51
7	.02230	.01590	51
8	.03566	.02077	51
9	.05180	.02507	51
10	.07055	.02925	51
11	.09153	.03266	51
12	.11483	.03635	51
13	.13869	.03932	51
14	.16468	.04273	50
15	.19037	.04649	49
16	.21580	.04961	46
17	.24090	.05264	46
18	.26808	.05543	44
19	.29321	.05813	44
20	.31822	.06133	44
21	.34378	.06621	39
22	.36567	.06715	38
23	.39119	.06987	38
24	.41538	.07211	38
25	.44095	.07574	38
26	.46152	.08260	32
27	.48080	.08405	31
28	.50500	.08866	31
29	.52821	.09423	31
30	.55177	.09978	31

The correlation matrices were obtained by using the PROC CORR computer program (SAS, 1985). The output for the exponential phase was presented in Table 2. It can be seen that the matrices is symmetrical along the diagonal of unity and hence the response surface model must also be symmetrical. Thus, the following model was constructed:

$$Z = B0 + B1(X + Y) + B2(X * X + Y * Y) + B3(X * Y)$$

where Z = Output variable associated with correlation between two ages, X, Y = Input variables associated with two ages, and B0, B1, B2, B3 = Regression coefficient associated with the intercept, linear, quadratic and crossproduct function of the two ages.

The PROC-RSREG computer program (SAS, 1985) was used to fit the response-surface model. The age-age correlations were transformed by taking a natural logarithmic transformation for the multiplicative error

TABLE 2. Correlation of volume growth between two ages during the early growth period.

Age	Age 3	4	5	6	7	8	9
3	1.00	.91	.77	.71	.64	.59	.56
4	.91	1.00	.94	.90	.83	.79	.75
5	.77	.94	1.00	.98	.95	.91	.87
6	.71	.90	.98	1.00	.98	.95	.91
7	.64	.83	.95	.98	1.00	.99	.96
8	.59	.79	.91	.95	.99	1.00	.99
9	.56	.75	.87	.91	.96	.99	1.00

model and were without transformation in the additive error model. Furthermore, the ages were transformed by either a square root or a logarithmic transformation. Therefore, each data set (age group 3-9 or 14-30) was fitted four times with varying transformations during model construction. It should be pointed out here that a square correlation matrices was also used for the linear growth phase (age period = 14 - 30) during modeling. However, the triangle above the diagonal was omitted in Table 3 to simplify typing and presentation.

RESULTS AND DISCUSSION

The response-surface model was able to explain more than 90% of the variation in age-age autocorrelation. The multiplicative error distribution model offers better fit than the additive error distribution model. However, the improvement in the overall R-square was only 1%.

The pattern of contribution to the R-square by linear, quadratic and crossproduct terms was similar between the additive error (Table 4) and the multiplicative error model (Table 5). The most important contributor to the R-square was the crossproduct terms. It explained from 58 to 66% of variation in the dependent variable. The least contribution was due to the linear term of the input variable. It explained less than 10% of the R-square during the exponential growing phase and explained absolutely nothing during the linear growing phase. The quadratic term, in general, accounted for a quarter of total variation.

Suitable transformation of age in X and Y of the response-model improves goodness of fit between data and model. The choice of taking a square root or a logarithmic transformation depends on the phase of growth development. During the exponential growth period, transformation of age by logarithm had a high R-square; but during the linear growth period the square root transformation was better.

The estimates of regression coefficient and its standard error were necessarily different between Table 4 and Table 5, because logarithmic

TABLE 3. Correlation of volume growth between two ages during the period of linear growth.

	Age																
Age	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
14	1.00																
15	.99	1.00															
16	.97	.98	1.00														
17	.95	.98	.99	1.00													
18	.92	.96	.98	.99	1.00												
19	.89	.94	.97	.98	.99	1.00											
20	.87	.92	.95	.97	.99	.99	1.00										
21	.85	.91	.94	.97	.98	.99	1.00	1.00									
22	.82	.88	.92	.95	.97	.98	.99	1.00	1.00								
23	.78	.85	.89	.93	.94	.96	.98	.99	1.00	1.00							
24	.75	.82	.86	.90	.92	.94	.96	.97	.99	1.00	1.00						
25	.71	.78	.83	.87	.89	.91	.93	.95	.97	.99	.99	1.00					
26	.72	.78	.82	.86	.87	.90	.92	.93	.95	.97	.98	.99	1.00				
27	.68	.75	.80	.84	.85	.87	.89	.91	.93	.95	.97	.98	1.00	1.00			
28	.64	.71	.76	.80	.81	.83	.85	.87	.90	.92	.94	.96	.98	1.00	1.00		
29	.58	.65	.70	.74	.75	.78	.80	.83	.85	.89	.91	.94	.96	.98	.99	1.00	
30	.53	.60	.65	.69	.70	.73	.75	.79	.81	.85	.87	.90	.94	.96	.98	1.00	1.00

TABLE 4. Comparison of response surface models for two correlation matrices from Tables 2 and 3.

Item	Growth period between ages	
	3 - 9	14 - 30
	Fitted by the square root of age	
	R-Square	
Total	0.9177	0.9419
Linear	0.1021	0.0009
Quadratic	0.2344	0.2778
Crossproduct	0.5812	0.6631
Parameter	Est. (Std. Dev.)	Est. (Std. Dev.)
B0	0.5905 (.4679)	0.9547 (.2385)
B1	0.1164 (.2718)	0.0200 (.0668)
B2	-0.3560 (.0545)	-0.1587 (.0065)
B3	0.6841 (.0470)	0.3103 (.0058)
	Fitted by the logarithm of age	
	R-Square	
Total	0.9550	0.9157
Linear	0.1253	0.0000
Quadratic	0.2212	0.2686
Crossproduct	0.6084	0.6471
Parameter	Est. (Std. Dev.)	Est. (Std. Dev.)
B0	0.8788 (.2116)	1.1062 (.6631)
B1	0.0417 (.4052)	0.0145 (.6508)
B2	-2.2892 (.2666)	-4.4381 (.2225)
B3	4.6516 (.2310)	8.7857 (.2206)

TABLE 5. Comparison of response-surface models for two correlations matrices from Table 2 and 3. Correlations were transformed by natural logarithm.

Item	Growth period between ages			
	3 - 9		14 - 30	
	Fitted by the square root of age			
	R-Square			
Total	0.9264		0.9507	
Linear	0.0926		0.0008	
Quadratic	0.2515		0.2908	
Crossproduct	0.5822		0.6590	
Parameter	Est.	(Std. Dev.)	Est.	(Std. Dev.)
B0	-0.2764	(0.2396)	-0.1142	(0.1129)
B1	0.0918	(0.1392)	0.0304	(0.0316)
B2	-0.1996	(0.0279)	-0.0834	(0.0031)
B3	0.3706	(0.0241)	0.1589	(0.0027)
	Fitted by the logarithm of ages			
	R-Square			
Total	0.9667		0.9238	
Linear	0.1158		0.0000	
Quadratic	0.2410		0.2807	
Crossproduct	0.6099		0.6430	
Parameter	Est.	(Std. Dev.)	Est.	(Std. Dev.)
B0	-0.1025	(0.0986)	-0.1500	(0.3240)
B1	0.0908	(0.1887)	0.1632	(0.3179)
B2	-1.2933	(0.1242)	-2.3314	(0.1087)
B3	2.5206	(0.1076)	4.500	(0.0980)

transformation was used for the dependent variable (i.e. age-age correlations) in Table 5, but not in Table 4. However, the positive sign for the B1 and B3 and the negative sign for B2 were consistent. Thus, regardless if the fitting error is additive or multiplicative, higher correlation is obtainable with greater crossproduct terms, but with smaller quadratic terms.

An interesting trend was also observed in the comparison of coefficients B2 and B3: the value of B3 was about twice as large as the absolute value of B2. Thus, the response-surface model for age-age correlation could be reduced to the following equation with some reduction in the total R-square:

$$Z = B0 + B1(X - Y)^2$$

It can be seen that this equation becomes Lambeth's model when X and Y are the logarithm of ages. The value of coefficient B0 and B1 of course are different from those given in Table 4 and 5, because the fitted models are not exactly alike.

As a stand development changed from the early exponential growing phase to maturing linear growth period, the linear component becomes diminished while the quadratic and crossproduct components become larger. It would be appropriate to consider different models and transformations separately for each phase of stand development. Significant contributions can be made to tree improvement program by forest biometricians in presenting a statistically sound and biologically meaningful model for the age-age autocorrelation so that the earliest age for selection can be decided to maximize genetic gain per unit of time and per unit of space.

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KEY WORDS: Yield, self-thinning, estimation, inventory, regeneration, climatic effects, pollution.

FINDING OUT AND TELLING

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it--in short, "finding out and telling." As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager to meet these challenges while protecting the environment is what research at North Central is all about.

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